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An integrated approach for climate-change impact analysis and adaptation planning under multi-level uncertainties. Part II. Case study

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ABSTRACT

In this study, a large-scale integrated modeling system (IMS) was applied for supporting climate change impact analysis and adaptation planning of the energy management system in the Province of Manitoba, Canada. The system was based on the integration of the fuzzy-interval inference method (FIIM), inexact energy model (IEM), and uncertainty analysis. Issues concerning energy management systems planning for cost-effective adaptation strategies under climate change were generated. Decisions of energy allocation, power generation and facility expansion within a multi-facility, multi-option, and multi-period context were obtained. Tradeoffs among system cost, climate change impact, system reliability and resilience were analyzed. The obtained solutions would be helpful for the adjustment or justification of the existing allocation patterns of energy resources and services, the long-term planning of renewable energy utilization, the formulation of local policies regarding energy consumption, economic development, and energy structure, the analysis of interactions among economic cost, system efficiency, emission mitigation, and energy-supply security, and the investigation of system vulnerability and responses towards various levels of impacts under climate change. Thus, IMS could provide an effective technique for decision makers in examining and visualizing integrated impacts of climate change on energy management systems as well as identifying desired adaptation strategies under multiple levels of uncertainties (i.e., the uncertainties associated not only with climate change impact analysis, but also with adaptation planning).

Contents

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1. Introduction

In Canada, sustainable utilization of renewable energy resources has been prioritized at multiple levels of jurisdictions, such as the Province of Manitoba, due to growing concerns from the public regarding greenhouse gas (GHG) emission, conventional fuel depletion, and energy expenditure growth [1–5,63–67]. This process is frequently affected by a number of economic, technical, environmental, legislational, and political factors and their interactions, posing many challenges for decision makers in the planning of energy management systems (EMSs) [6–9]. These factors are normally subject to a variety of uncertainties, leading to many complexities in relevant decision-making processes. Such complexities may be further multiplied by multi-period, multi-facility and multi-objective features as well as system dynamics. Furthermore, a number of system processes and/or factors (e.g., renewable energy availability and energy end-user demand) are greatly affected by climate change to an uncertain degree, further amplifying the complexities. Thus, system analysis techniques are desired to assist in formulating long-term energy management and allocation plans under multiple levels of uncertainties. This will be helpful not only for analyzing tradeoffs among various socio-economic, energy-related, and environmental objectives, but also for providing effective adaptation schemes in responding to varied impact levels of climate change in Canada, particularly the provinces that are highly dependent on renewable energies such as the Province of Manitoba.

In the past decades, many researchers have made great efforts in investigating climate change impacts on multiple scales of energy management systems in many regions across the world [10–15]. For instance, Peramunetilleke [11] assessed the impacts of climate change on Sri Lanka's hydroelectric production. Bhartendu and Cohen [16] evaluated the impacts of climate change on energy demands for residential heating and cooling in the Province of Ontario, Canada. Allen and Christensen [17] briefly reviewed detailed implications of climate change and suggested that a diverse range of issues would contribute to this process. Sinyak [18] examined impacts of climate change on various EMSs. Sutherland [19] qualitatively analyzed potential impacts of climate change on a number of energy-intensive industries in US. Breslow and Sailor [20] investigated impacts of climate change on average wind speed and, hence, on wind power generation in US. A series of GCM outputs from the Canadian Climate Center and the Hadley Center were used to provide a range of possible variations in seasonal mean wind magnitude. Potential impacts of climate change on heating and cooling energy demands were investigated by means of several building energy simulation models under hourly weather scenarios and were applied to the Zurich–Kloten area of Switzerland [21]. Gaterell and McEvoy [14] examined effects of climate change uncertainties on performance of energy conservation measures. Christenson et al. [13] investigated the impacts of climate change on energy demand of residential buildings in Switzerland by means of the degree-days method. Mirasgedis et al. [22] adopted a regional climate model, PRECIS, to predict future climatic conditions under different emissions scenarios. The predicted data were used as inputs to a multiple regression model to examine sensitivities of electricity demand in Greece. Pryor and Barthelmie [23] qualitatively assessed impacts of climate change on power generation from wind energy, particularly on operation and maintenance of several wind farms. Based on a qualitative method, Whitmarsh [24] investigated various behavioural responses to the impacts of climate change on many energy activities. Guan [25] attempted to assess the impacts of climate change on the building environment through the combination of weather-data forecasting and building simulation techniques. Bassi and Baer [26] employed an integrated modeling approach to carry out a country-wide and cross-sector analysis of the interactions among Ecuador's energy, social, economic and environmental sectors under climate change. Isaac and van Vuuren [27] assessed potential energy use for future residential heating and air conditioning under climate change. The results indicated impacts on heating and cooling individually would be considerable, with heating energy demand decreasing by 34.0% worldwide by 2100 as a result of climate change, and air-conditioning energy demand increasing by 72.0%.

Under a series of climate change impacts, adaptation plans need to be systematically considered by decision makers. Previously, a large number of studies were undertaken on adaptation planning towards climate change in water resources management, watershed management, forest management, and energy management, as well as many other areas [28–37]. For example, Huang et al. [38] proposed an inexact-fuzzy multi-objective programming model for adaptation planning of land resources management in the Mackenzie Basin under changing climatic conditions. Stakhiv [39] suggested that policy makers and water resource managers should be aware of the evolving information on climate change impacts as an activity that was preparatory to sound decision making on current water resource management actions. Tol et al. [28] made a thorough investigation on studies related to climate change adaptation. Since climate change poses significant challenges for water resource management in Canada, de Loë et al. [40] discussed issues related to the selection of proactive and planned adaptation measures to water supply systems in the near future. Næss et al. [41] examined the adaptation of infrastructural institutions under climate change in Norway. Two municipalities were used as examples for investigating institutional responses to floods under climate change. Dessai and Hulme [42] presented an assessment framework for supporting the identification of adaptation strategies that were robust to climate change uncertainties. Osbahr et al. [43] explored cross-scale dynamics in coping with and adjusting responses towards climate change based on qualitative data from a real-world case in Mozambique. Paavola [44] examined farmers' livelihood responses and vulnerability to climatic variability in Morogoro, Tanzania. van Aalst et al. [45] proposed a CRA (community risk assessment)-based method for identifying effective adaptation strategies to climate change. More recently, Hoffmann et al. [46] empirically examined the determinants of adaptation measures/policies under climate change. Bryan et al. [35] advanced adaptation strategies for farmers in South Africa and Ethiopia as responding actions to climate change and analyzed the factors influencing their decisions. Deressa et al. [47] identified major strategies under climate change in the Nile Basin of Ethiopia. Reidsma et al. [48] analyzed the farmers' adaptation measures to climate change in the European Union.

Particularly, a number of studies were undertaken for examining optimal strategies under climate change in energy sectors across the world. For example, Simeonova [49] analyzed a variety of policies and measures as potential adaptation plans towards climate change in the energy sectors of many central and eastern European countries. Matondo et al. [50] examined the impacts of climate change on hydrological regimes, water resources management, and hydropower generation in Swaziland through the adoption of GCM downscaling results (including rainfall, potential evapotranspiration, and air temperature) as inputs to a rainfall-runoff model. Ruth and Lin [51] explored potential impacts of climate change on the consumptions of natural gas, electricity, and heating oil by residential and commercial sectors in the state of Maryland of US. Time series analysis was then used to quantify relationships between historical temperature and energy demand. A dynamic computer model based on those relationships was used for simulating future energy demand under a range of energy prices, temperatures, and other driving factors. Mansur et al. [52] adopted a national energy model of fuel choice to generate climate change adapta-

tion strategies at both households and firm scales. They suggested that increasing electricity consumption for space cooling would be observed with a reduction in energy consumption for space heating under climate change. Overall, energy-related expenditures would likely increase in America, resulting in welfare damages that would increase as temperatures rise due to climate change. Jenkins et al. [53] attempted to quantify how climate change will have a direct effect on heating and cooling energy use in future office environments. The results confirmed the importance of demand-side management before assessing the supply-side opportunities under extreme climatic events. The study also highlighted the importance and possibilities, of adapting to future climates, and the benefits of promoting heating-dominated buildings instead of cooling-dominated ones. Weisser et al. [54] used a qualitative analysis method to explore the conditions under which nuclear power could adapt to climate change over a long term period.

The previous studies were conducted in a number of locations either on climate change impact analysis or adaptation planning, there were no reports on identifying optimal adaptation strategies under varied impact levels of climate change, particularly in a region/province (such as the Province of Manitoba in Canada) that is highly dependent on renewable energy resources. In this province, there is no clear evidence that climate change impacts will be significant or predominantly negative on the hydrological regimes and climatic conditions which are important for energy supply and power generation. Particularly, analyses of such impacts, as well as advancement of subsequent adaptation actions, are subject to multiple levels of uncertainties which have not been previously addressed in EMSs planning. Since energy development is of great significance to the economic development and bilateral/international trade in this province, there are quite a number of challenges confronted by local decision makers [55], such as: (i) how to exploit hydropower and other renewable energy sources in an optimal pattern that could be considered as the baseline in the province? (ii) how to evaluate and address impacts of climate change on the utilization of renewable energy sources such as hydropower and wind energy? (iii) how to evaluate and address impacts of climate change on end-user energy demand? (iv) how to get the coupled impacts of climate change on both the demand and supply sectors? (v) how to interactively reflect expertise opinions with imprecise information during the process of decision making? (vi) what, if any, actions need to be undertaken as adaptation measures towards climate change impacts and what will these actions be to improve system resilience under climate change? (vii) what are the major differences between energy allocation/consumption patters under the business as usual (BAU) case and the one considering climate change impacts? (viii) how to effectively address uncertainties associated with climate change impact analysis? and (ix) how to effectively analyze tradeoffs among energy productions, EMS reliabilities, economic costs, and climate change impact levels in the province? Until now, there were no reported studies that could link adaptation planning with climate-change impact analysis and could address multi-level uncertainties associated with impact analysis as well as the subsequent adaptation planning.

In order to answer these questions in the province, systems analysis methods that represent the integration of climate change impact analysis and adaptation planning are imperative. Therefore, the objective of this research is to systematically analyze the impacts of climate change on the entire EMS of Manitoba under multiple levels of uncertainties, and then identify optimal adaptation strategies in response to varied climate change impact levels. This will be based on an integrated energy modeling system (IEMS) through incorporating a fuzzy-interval inference method (FIIM) and an inexact energy model (IEM) into a general modeling framework (Part I: Methodology). The linkages between climate change impact levels and necessary adaptation actions in Manitoba will be reflected. Interactions among various system components, objectives and constraints will be addressed. Issues concerning cost-effective energy allocation, EMS resilience improvement, and uncertainties reflection, as well as trade-off analysis between economic costs and EMS reliabilities will be tackled. Decisions of facility operation and expansion, and resource allocation within a multi-facility, multi-option, and multi-period context will be obtained in response to varied climate change impacts. The obtained results will provide useful decision alternatives for Manitoba's energy management within a long-term period.

2. Overview of the study area

2.1. The Province of Manitoba

Manitoba is the easternmost one of the three Prairie Provinces in western Canada which has an area of 649,950 km^2 [56]. It is bordered by the Province of Saskatchewan to the west, the Province of Ontario to the east, the Territory of Nunavut to the north, and the US states of North Dakota and Minnesota to the south. It has a population of 1,213,815 (according to 2009 estimates), with more than half located within the Winnipeg Capital Region [57–59]. Winnipeg which has Canada's 7th largest municipality is Manitoba's largest and capital city. The province has abundant water resources and hydropower capacity. The major watercourses in the province include the Red River, the Assiniboine River, the Nelson River, the Winnipeg River, the Hayes River, the Whiteshell River, and the Churchill River, making it one of the largest hydropower producers in Canada. Most of these rivers originate from hilly and rocky areas. As Manitoba is far removed from the cushioning influences of both mountain ranges and large bodies of water, and because of its generally flat landscape, it is exposed to numerous complex weather systems and therefore is sensitive to changing climatic conditions. This causes a large number of uncertainties and risks in the utilization of many natural resources (e.g., hydropower, solar and winder energies) which are significantly dependent on a variety of climatic factors.

Manitoba's economy relies heavily on tourism, energy, agriculture, oil, minerals, mining, and forestry. Agriculture is vital to Manitoba's economy and is mainly found in the southern half of the province. In this province, transportation and warehousing contributes approximately CAD$ 2.20 billion to the province's total GDP. The total employment in the industry was estimated at 34,500 in 2009 [60]. The province has road, rail, air, and marine components in its transportation industry. The Trans-Canada Highway, built between 1950 and 1971 crosses the province from east to west. Trucks haul 95.00% of all land freight in Manitoba, and trucking companies account for 80.00% of Manitoba's merchandise trade to the United States. Totally, CAD$ 1.18 billion of Manitoba's GDP directly or indirectly comes from trucking. Around 33,000 people work in the trucking industry. Domestic and international bus services from the Winnipeg Bus Terminal are offered by Greyhound Canada and Jefferson Lines. Manitoba has two Class-I railways, i.e., the Canadian National (CN) Railway and the Canadian Pacific (CP) Railway. Winnipeg is centrally located on the main lines of both of these two continental carriers, and both companies maintain large inter-modal terminals in the city. Totally, CN and CP operate a combined 2439 km of track within Manitoba. Numerous small regional and short-line railways exist in the province, including the Hudson Bay Railway, the Southern Manitoba Railway, the Burlington Northern Santa Fe Manitoba Railway, the Greater Winnipeg Water District Railway, and the Central Manitoba Railway. Altogether, they operate approximately 1775 km of track within the province. The Winnipeg James Armstrong Richardson International Airport is one of only a few 24-h unrestricted airports in Canada and is part of

the National Airports System (NAS). It has a broad range of passenger and cargo services and served over 3.50 million people in 2007, which is over the maximum capacity of 600,000. The airport handles approximately 140,000 tonnes of cargo annually, which makes it the 3rd largest in the country. Air Canada Cargo and Cargo-jet Airways use the airport as a major hub for national traffic. The Port of Churchill is Canada's main window to the Arctic Ocean, to Russia, and to inland China. This port is nautically closer to ports in Northern Europe and Russia than any other ports in Canada. It is the only Arctic deep water port in Canada and a part of the shortest shipping route between North America and Asia. The port is linked by the Hudson Bay Railway. Grain represented 90.00% of the port's traffic in the 2004 shipping season. In that year, over 600,000 tonnes of agricultural products were shipped through the port [60].

2.2. Current energy management system in the Province of Manitoba

Manitoba is currently a net importer of non-renewable energy resources but is poised to become a Canadian leader in the production and consumption of renewable ones. In the past decades, Manitoba has been aggressively pursuing the development of economically feasible and technologically efficient measures/alternatives to reduce the province's high dependence on imported fossil fuels. According to Manitoba Hydro [61], about 74.00% of the energy consumed by Manitoba in 2004 was from the imported non-renewable energy resources. The remaining 26.00% was renewable hydro-generated power produced domestically (Fig. 1). In the same year, 98.30% of the domestically produced electricity was hydro-generated in the province. The remaining (1.70%) was generated by coal and natural gas. On average, 98.00% of the domestically produced electricity has been renewable since 1980, the majority of which has been hydro-generated power. In 1980, 235,600 TJ of energy was consumed in the province. This amount increased to 255,973 TJ in 2004. The total energy consumption in Manitoba from 1980 to 2004 and the projected energy consumption to 2010 are presented in Fig. 2. It is believed that a dramatic drop in natural gas consumption in the province's pipeline sector partially caused the decrease in energy consumption since 1996. Warmer weather due to climate change in the past decades has also reduced overall energy requirements in the province.

Since 2000, over 70,000 homeowners in Manitoba have benefited from a number of energy efficiency programs, such as the Low-Interest Loans, the EnergGuide Home Visits, and the Manitoba Earth Power Program. Also, the province is considering replacing its high-efficiency gas furnace incentives with a change to its Building Codes. In the province, energy intensity dropped greatly over the period from 1981 to 2004 (from 10.00 to 7.30 MJ/$). This represents a 27.00% improvement in the energy intensity over the 24-year period. The projected energy intensity for 2010 would be 6.80 MJ/$ real GDP, which is a 7.00% decrease over the 2004 level. In the province, approximately 99.00% of the energy requirements for on-road transportation are met with refined petroleum products (RPPs) [57–59,62]. With the increasing adoption of renewable energy resources, this sector is believed to have experienced a decrease in fossil fuel consumptions through improving vehicle efficiencies and acceptance of hybrid vehicles. Gasoline, diesel and the total RPPs consumption trends in Manitoba from 1980 to 2004 (with projections to 2010) are displayed in Fig. 3. As the figure indicates, gasoline consumption has increased steadily since 1989, due to the considerable rise in larger vehicles like SUV and vans in the 1990s. Because Manitoba relies largely on a trucking economy, the amount of diesel being consumed is more erratic than gasoline consumption. Even so, conventional diesel consumption is expected to decrease from 2006 to 2010 with the adoption of biodiesel. The province is currently considering a number of significant investments in biodiesel production. In this province, the passenger-vehicle energy intensity (the ratio of annual gasoline consumption to the number of passenger vehicles) was 0.11 TJ/vehicle. By 2004, this value had dropped to 0.09 TJ/vehicle, indicating a 22.00% improvement over this time period. Since the onset of dramatically increased oil prices in 2003, Manitoba has been experiencing declining SUV sales. Correspondingly, this has improved the passenger-vehicle energy intensity due to a shift to more fuel-efficient passenger vehicles.

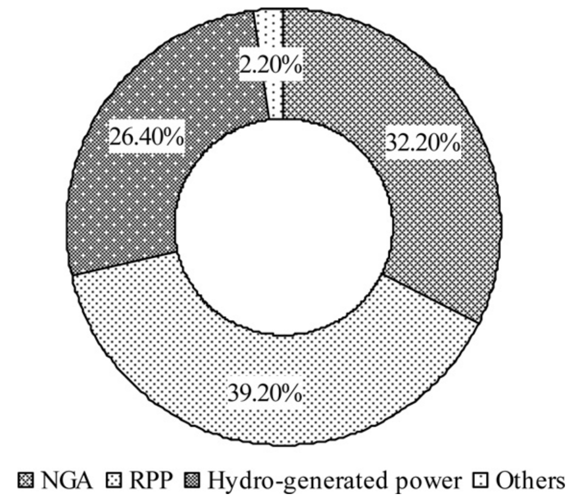

Fig. 1. Energy consumption by fuels in the province of Manitoba in 2004.

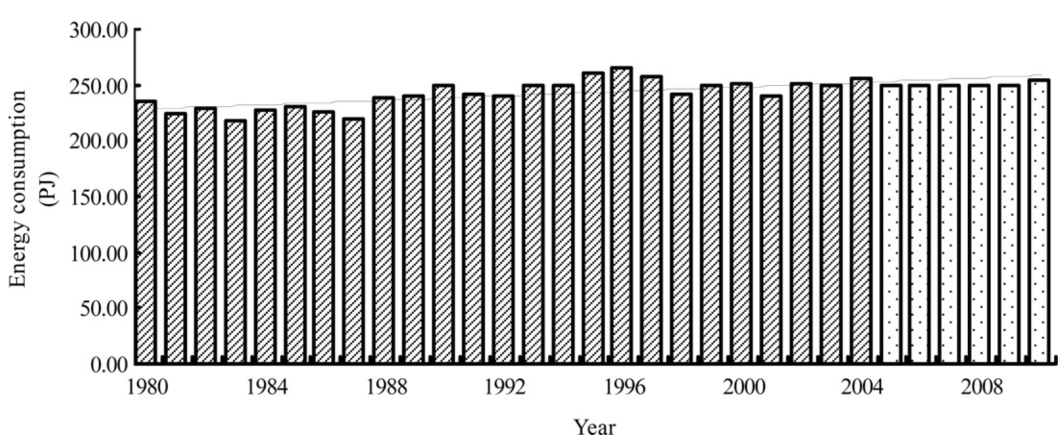

Fig. 2. Energy consumption in Manitoba over 1980–2010 (actual consumptions from 1980 and projected consumptions 2005–2010).

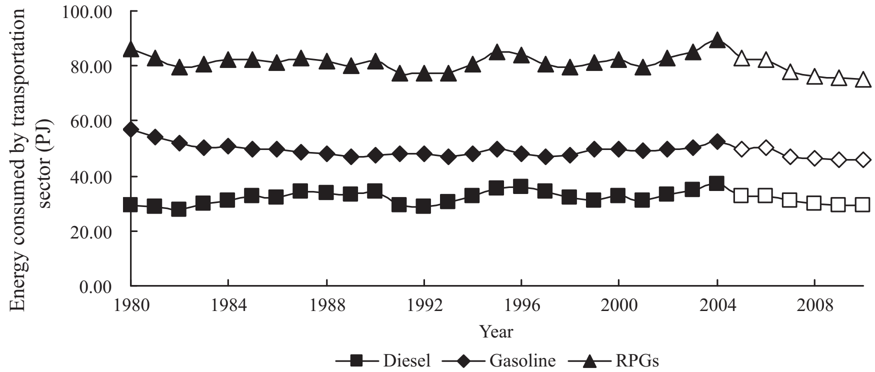

Fig. 3. Gasoline, diesel and RPPs consumption in Manitoba over 1980–2010.

In terms or energy consumption in the province, a diversity of energy resources is provided, including fossil fuels and renewable energy resources. In detail, the industrial sector in the province accounted for about 20.00% of the total energy consumed in Manitoba from 1980 to 2004. During the same period, energy consumption in the industrial sector increased slightly due to the synthetic impacts of industrial development and energy-utilization efficiency improvement. Natural gas was the largest fuel source in the industrial sector (around 43.00%) until the mid-1990s, when electricity surpassed natural gas as the predominant energy source. Since then, natural gas consumption has decreased to 40.00% in the 1990s and early 2000s. In contrast, the sector's demand for electricity has increased from 33.00% of the total consumption in the early 1980s to 45.00% in the late 1990s and early 2000s. The demand for RPPs dropped from 15.00% of the total energy consumption in the early 1980s to approximately 8.00% in the late 1990s and early 2000s. The commercial sector consumes about 19.00% of the total energy in Manitoba. Since the early 1980s, natural gas has consistently met 60.00% of commercial energy requirements. In detail, the period from 1993 to 2004 shows a 23.00% increase in electricity consumption (from 11.30 to 13.90 PJ). In Manitoba, energy consumed in the residential sector accounts for about 18.00% of the total energy consumed in the province. Since the early 1980s, consumptions of RPPs and natural gas have dramatically decreased in the residential sector. However, these energy resources are still the necessary fuels for many remote communities in Manitoba, regardless of their comparatively high economic and environmental costs. Natural gas consumption experienced an apparent increase from 23.60 PJ in 1980 to 28.60 PJ in 1990. From 1990 to 2004, natural gas consumption decreased by approximately 18.00% (i.e., 5.20 PJ). Meanwhile, electricity consumption experienced a steady increase from 11.80 PJ in 1980 to 21.70 PJ in 2004. The decrease of natural gas consumption since 1990 contributed to an increase of electricity consumption. In addition, residential energy intensity (the ratio of residential energy consumption to population) was 41.00 TJ/1000 persons in 1981. This value had dropped to 38.90 TJ/1000 persons by 2004, representing a 5.00% improvement over the period of 1981–2004. Many figures indicate that residential energy intensity in Manitoba has been decreasing since 1990 due to the implementation of the Residential Building Codes in 1994, as well as the efforts by homeowners to improve the energy efficiency of their homes. The agricultural sector uses about 9.00% of the total energy consumed in Manitoba. This sector has experienced a rise in energy consumption from 15.30 PJ in 1980 to 23.70 PJ in 2003. In total, RPPs consistently meet over 72.00% of the energy requirements in the agricultural sector, and electricity accounts for approximately 25.00% of this sector's total energy consumption.

In the province, although fossil fuel is the dominant resource, encouraging energy-consumption trends around renewable or green energy resources are regarded as provincial targets. Presently, potential renewable energy sources include hydro-generated power, geothermal energy, biofuels, and solar and wind energies. Hydro-generated power has been the primary source of renewable energy in Manitoba. The ratio of consumed renewable energy to the total consumed energy over the period of 1980–2004, with projections to 2010, is displayed in Fig. 4. As indicated in this figure, the ratio of consumed renewable energy to total consumed energy was 18.00% in 1980. In 2004, the ratio increased to 27.00%. It is expected that the ratio will reach 30.00% by 2010 with the transition from non-renewable energy resources to hydro-generated power, biofuels, and solar and wind energies. Also, from 1980 to 2002, the ratio of renewable energy produced to total energy consumed increased from 29.00 to 41.00%. Such a growth was mostly attributed to the boost in hydro-generated power exports. However, as indicated from this figure, there was a significant decline in the ratio of renewable energy produced to total energy con-

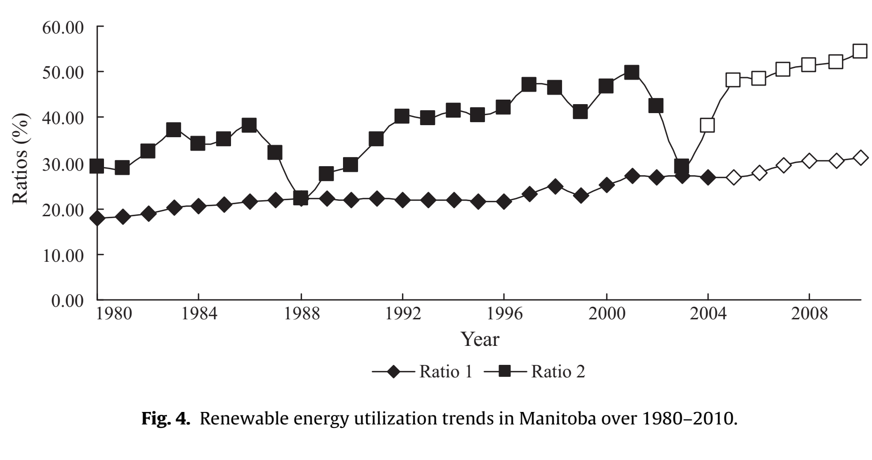

Fig. 4. Renewable energy utilization trends in Manitoba over 1980–2010.

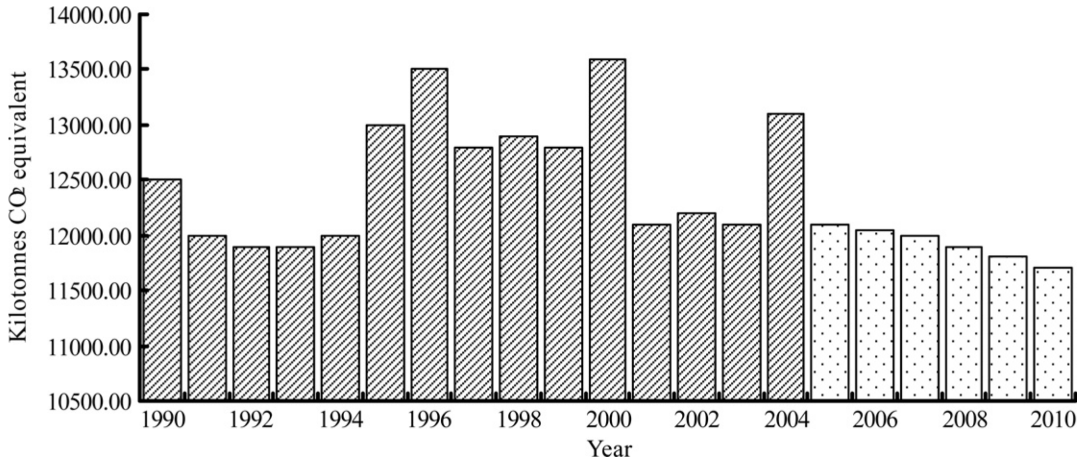

Fig. 5. Energy-related CO_2 equivalent emissions in Manitoba over 1990–2010.

sumed in the late 1980s and in 2003. During those periods, the province underwent drought conditions and significant reductions in hydro-electric power generation capacities occurred, reflecting the vulnerability of the EMS to climatic variations.

In the Province of Manitoba, wind-generated electricity can be effectively combined with hydro-generated power. When winds are blowing, wind turbines produce electricity, enabling hydro dams to retain higher reservoir levels and, therefore, conserve hydro-generated power. When the winds are calm, stored water is released to generate additional hydro-generated power, offsetting the reduction in wind-generated output. The geographic distribution of wind farms results in less overall wind-generating downtime and improved wind system predictability. Preliminary studies show that there are rich in wind resources across widely dispersed areas of Manitoba. The 99.00 MW St. Leon wind farm located in south-western Manitoba is this province's first wind farm. Over the next decade, a number of subsequent wind farms are expected to be developed, collectively producing 1,000 MW of electrical power. The consumption of non-renewable, fossil fuels contributes significantly to GHG emissions in the province. According to Environment Canada's 1990–2001 GHG inventories, the energy sector was responsible for 59.00% of Manitoba's total GHG emissions. Fig. 5 shows estimates of the annual carbon dioxide (CO_2) emissions associated with fossil fuel consumption in Manitoba's energy sector from 1990 to 2001, with projections to 2010. Energy-related CO_2 emissions closely follow the energy consumption trend, which is projected to rise over the period from 2005 to 2010. The ratio of renewable to total energy consumed is also expected to increase due to the adoption of advanced technologies and renewable energy resources. The anticipated increase in the ratio of renewable to the total consumed energy will help reduce energy-related CO_2 emissions in Manitoba. Fig. 6 shows the CO_2 emission intensities (energy-related CO_2 emissions per \$ 1.00 billion CAD of real GDP) from 1990 to 2001, along with projections to 2010. The CO_2 intensity in 1990 was 461.00 Kt CO_2 equivalent/\$1 billion real GDP. In 2001, this amount decreased to 366.00 Kt CO_2 equivalent/\$1 billion real GDP, indicating a 21.00% improvement over the 12-year period. The projected intensity in 2010 would be 328.00 Kt CO_2 equivalent/\$ 1 billion real GDP, representing a 10.00% improvement over the 2001 levels.

Currently, hydropower is Manitoba's largest source of provincially supplied renewable energy. Manitoba Hydro is a provincial crown corporation that has fourteen hydropower generation stations, two thermal plants, and four diesel generation sites (for providing energy to a few remote communities). Displacement of fossil-fuel based electricity generation outside of Manitoba with further development of Manitoba's hydropower resources has been identified as one of the least costly means by which Canada can reduce its GHG emissions. Manitoba's hydraulically generated electricity is a low emitter of GHG, particularly when compared to fossil fuels such as natural gas and coal. Due to its high dependence on various climatic conditions, however, hydropower generation is considered a sensitive technology that is vulnerable to climate change. Thus, climate change will have an impact on Manitoba's hydropower resources, as well as its current energy management system. For example, it is believed hydrological regimes will be

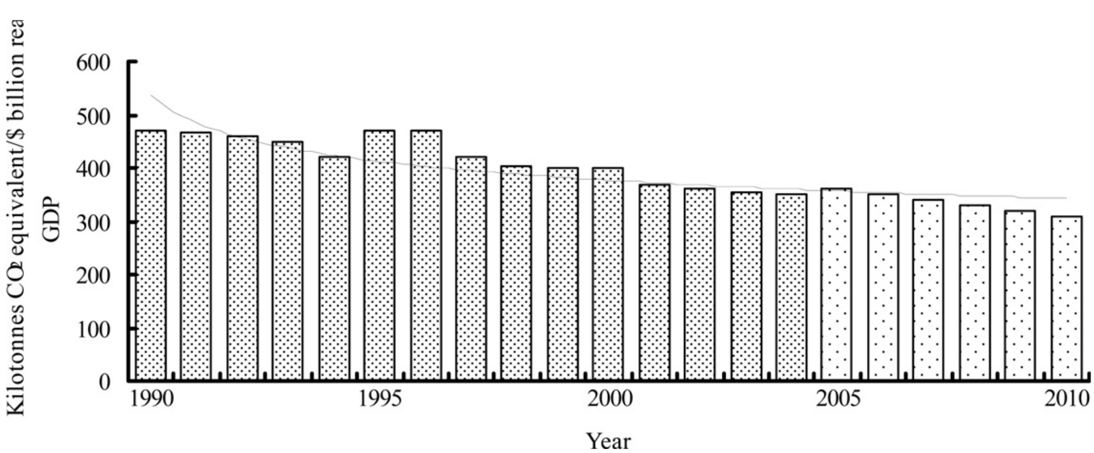

Fig. 6. Energy-related CO_2 equivalent emissions intensity in Manitoba over 1990–2010. *Note*: actual consumptions from 1980 and projected consumptions 2005–2010.

influenced by climate change, probably leading to a series of unexpected results such as (a) increasing precipitation rates, (b) frequent occurrences of extreme events, and (c) changing patterns of precipitation (e.g., longer dry periods). These are of great significance to hydropower generation in the province and, thus, will cause increasing concern over energy security and energy-shortage risks in the Province of Manitoba over a long-term period. However, there is no clear evidence that climate change impacts will be significant or predominantly negative on the hydrological regimes and weather conditions in the province. Accordingly, identification and analysis of such impacts, as well as the subsequent adaptation actions are naturally subject to a variety of uncertainties, which need to be systematically reflected and addressed in the long-term planning of the energy management system in the Province of Manitoba.

According to the nature of the current energy sector in the province, major energy supply options considered in this research include fossil fuel [such as coal, oil (including gasoline, diesel, and fuel oil), and natural gas] and renewable energy resources (such as hydropower and wind energy). These options provide a variety of energy supplies to meet the demands of domestic and external end-users. Likewise, end-users in this research are disaggregated into a set of sub-sectors, such as residential, commercial, industrial and transportational ones. Since electricity production in Manitoba is primarily from large-scale power plants, particularly hydropower stations, conversion and processing technologies considered in this research mainly refer to those for large-scale electricity generation. Normally, adoption and expansion of these technologies depends on objectives of the decision-making process. If greater importance is attached to economic requirements, the cheapest solutions would be generated; on the other hand, when the goal is to reduce pollutant emissions, the most environmental-friendly technologies would be obtained. A number of facilities and the associated technologies, such as conventional thermoelectric plants, combined cycle plants, photovoltaic panels, and micro-turbine systems, are responsible for intermediate conversion of energy resources to electricity at a smaller scale, which are not employed by the current power generation system in Manitoba. However, in order to maintain possible expansion of the modeling structure, these could be potentially considered in this research. Electricity exports to neighbouring provinces and the United States are also considered in order to determine future expansions of electricity-production capacities in Manitoba. Emissions from energy activities could be quantified and curbed below a certain tolerance threshold through the addition of related inequality constraints when formulating planning models for Manitoba. The time frame of the model is set to reflect the dynamics of the energy management system in the study province, which includes nine periods starting in 2003 and ending in 2028. There are five years in each period, which is named by the middle year of that period (i.e., "period of 2005" denotes the period from 2003 to 2007, while "year of 2005" merely represents that year).

2.3. Uncertainty analysis

In the Province of Manitoba, in fact, all of energy-related processes and factors are influenced by changing climatic conditions. Among them, end-user demands, renewable energy resources and the corresponding utilization facilities are the most sensitive and vulnerable ones. For instance, availabilities of renewable energy resources (e.g., hydropower and wind energy) are highly dependent on the statistics (e.g., min, peak and mean values as well as variance) of many meteorological variables that might fluctuate within a certain range due to climate change. Such variations of renewable energy availabilities would then affect operating statuses of relevant facilities, resulting in changes in their energy outputs. Similarly, in responding to variations of climatic factors/conditions, such as temperature, solar radiation, and humidity, end-user demands for space heating, water heating, and space cooling would correspondingly vary over a certain range. Apparently, these impacts would not affect an individual energy sub-sector (e.g., energy demand and production) in an isolated way. Instead, they interact with each other and, thus, would cause an integrated impact on the entire EMS. Such an integrated impact over a long-term planning period needs to be systematically analyzed by decision makers in order to discern the most optimal adaptation schemes for the entire EMS under climate change. However, such a task is difficult due to a variety of uncertainties associated with changing climatic conditions as well as our subjective judgments towards impacts. For example, due to the lack of sufficient information related to the evaluation guidelines (e.g., impact levels), fuzziness is always associated with the process of impact identification and integration, which is normally caused by vague and imprecise linguistic terms. Correspondingly, the evaluation of occurrence chances of climate change and their consequences on EMSs is also subject to uncertainties and is difficult to be handled through conventional methods. This implies that planning activities for EMSs would be misled into a deviated or even false direction without a comprehensive consideration over the integrated impacts of climate change. Moreover, there is a variety of uncertain information associated with decision process, which can only be expressed as interval numbers without known distributions. Such uncertain information need to be effectively incorporated into the planning process and the obtained decision alternatives, which represents a different level of uncertainties compared with those implied in climate change analysis. Therefore, in this research, the integrated climate change impacts will be incorporated into the modeling framework to facilitate identifying adaptation plans with increased robustness under various changing conditions. Specifically, a fuzzy-interval inference method (FIIM) and an inexact energy model (IEM) will be developed and then integrated into a general modeling system (IEMS) as well as applied to the Province of Manitoba (IEMS – Manitoba).

3. Result analysis and discussions

3.1. Integrated impacts of climate change on Manitoba's energy management system

In this research, in order to demonstrate the applicability of the proposed integrated modeling system as well as the inexact energy model in the province of Manitoba, a scenario will be proposed. The impacts of climate change on energy supply and demand will be addressed. In this research, the scenario will be developed based on the following assumptions: (a) energy demands in the province are sensitive to climate change and are assumed to increase by 4.50%, and (b) for the impact of climate change on electricity generation facilities, the energy availability factors decrease by 10–15%. Correspondingly, it could be found from the companion paper (Part I: Methodology) that the impact level of climate change on end-user demand would be partly "medium-to-high" (with a membership grade of 0.5) and partly "high" (with a membership grade of 0.5). Similarly, it could be calculated based on the methodology in the companion paper (Part I: Methodology) that the impact level of climate change on the electricity generation sub-sector would be fully "low-to-medium" (with a membership grade of 1) under the lower bound and fully "medium" (with a membership grade of 1) under the upper bound. Thus, there are four combinations of the antecedents (i.e., four rules had to be analyzed under lower and upper bounds): (i) the impact level for end-user demand is "medium-to-high" and the corresponding impact level for the electricity generation sub-sector is "low-to-medium" (i.e.,

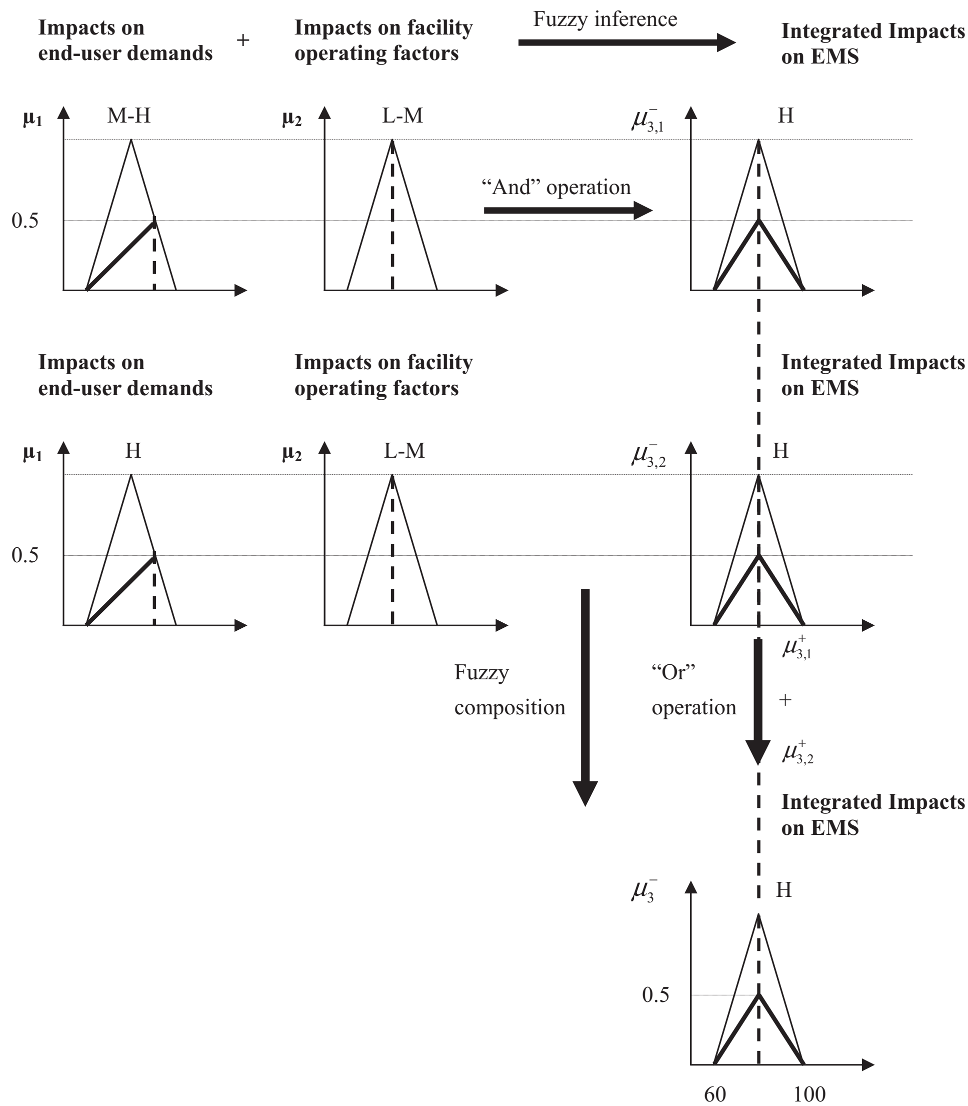

Fig. 7. Integrated climate change impacts on an EMS (lower bound).

lower bound), (ii) the impact level for end-user demand is "high" and the corresponding impact level for the electricity generation sub-sector is "low-to-medium" (i.e., lower bound), (iii) the impact level for end-user demand is "medium-to-high" and the corresponding impact level for the electricity generation sub-sector is "medium" (i.e., upper bound), and (iv) the impact level for end-user demand is "high" and the corresponding impact level for the electricity generation sub-sector is "medium" (i.e., upper bound).

The input and output data were analyzed in the inference process as shown in Figs. 7 and 8. The fuzzy "AND" operation was applied to the rule's antecedent to determine its consequence [i.e., $\mu_{\text{IIL}} = \text{Min}\ (\mu_{\text{EIL}}, \mu_{\text{SIL}})$] according to the rule base as shown in the companion paper (Part I: Methodology). In other words, the minimum degree of the membership grade of the two input factors (impact levels for end-user energy demand and electricity generation sectors) was given to the output integrated impact level. Specifically, in rule 1, $\mu^-_{3,1} = \text{Min}(\mu_1, \mu_1) = (0.5, 5) = 0.5$, in rule 2, $\mu^-_{3,2} = \text{Min}(0.5, 5) = 0.5$, in rule 3, $\mu^+_{3,1} = \text{Min}(0.25, 1) = 0.25$, and in rule 4, $\mu^+_{3,2} = \text{Min}(0.5, 1) = 0.5$. The outputs from the inference procedure, which were also the inputs for the composition process, became four scaled down fuzzy integrated climate change impact values [68]. In the composition process, the fuzzy "OR" operation was applied to the four fuzzy values (i.e., two of them under lower and upper bounds). Thus, the four fuzzy values were superimposed to obtain the final fuzzy integrated impact levels. The final level would be "high" with a membership grade of 0.5 under this scenario, and the crisp final value was obtained by calculating the centroid of the fuzzy impact value as 80. As a result, the suggested adaptation action would be "take full actions for mitigating climate change impact in the region" according to the results presented in the companion paper (Part I: Methodology). Based on the results of the integrated impact level, a certain series of adaptation actions should be undertaken for mitigating the effects of climate change on the EMS in the province of Manitoba.

3.2. *Optimal strategies under BAU case and climate change*

3.2.1. *The overall system costs*

Adaptation schemes under this scenario can be obtained for comparing energy allocation patterns under the BAU case and the one with the consideration of integrated climate change impacts. The objective function values and their variations compared with the BAU case are presented in Fig. 9. As reflected in the uncertain impacts of climate change, energy related expenditure variations would be mainly observed in residential, commercial, and electricity generation sub-sectors. In detail, the total expenditure in

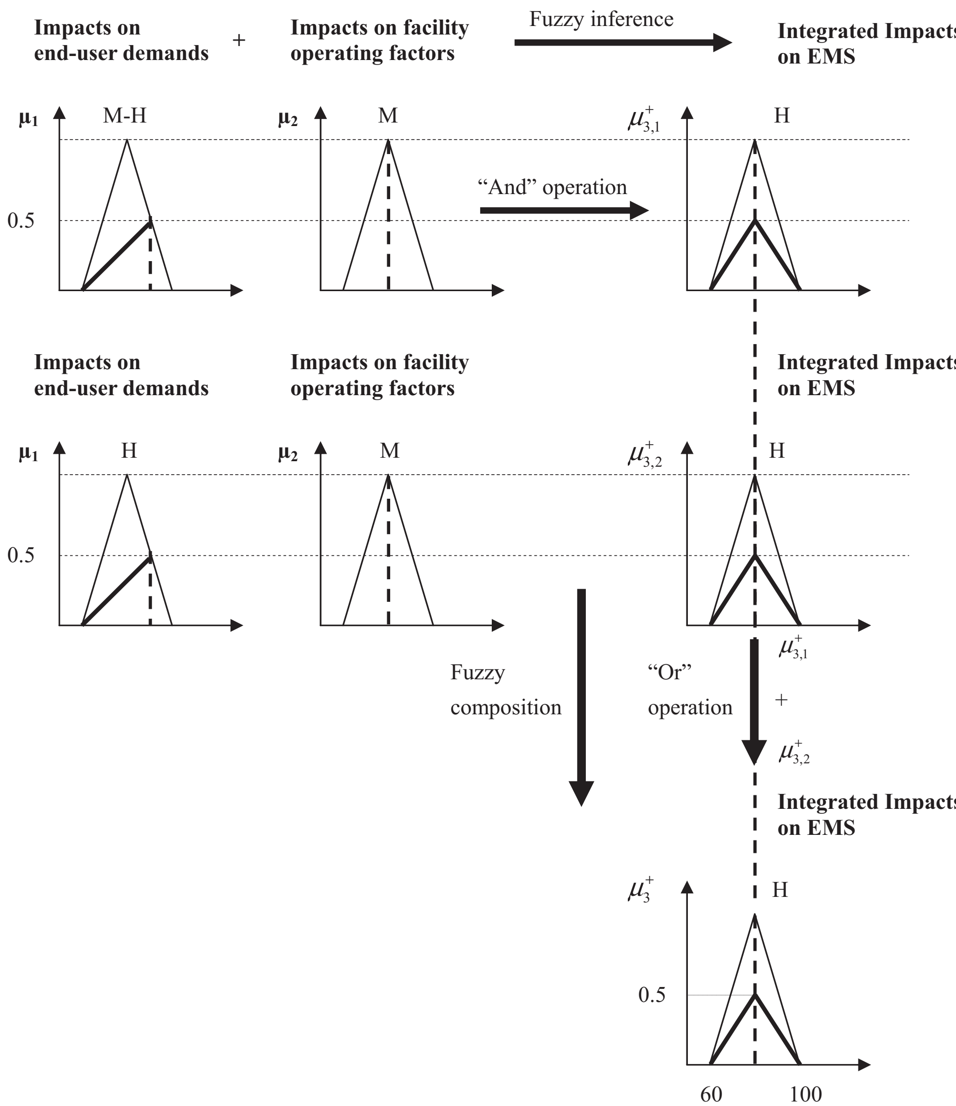

Fig. 8. Integrated climate change impacts on an EMS (upper bound).

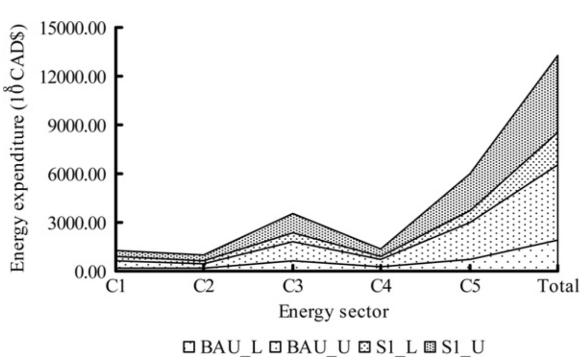

Fig. 9. Energy related expenditures under BAU case and climate change.

residential sector would increase from CAD [215.19, 428.97] to [222.15, 442.80] $\times 10^8$, representing an increment of 3.23 and 3.22% under lower and upper bounds (Table 1). Similarly, those expenditures associated with commercial and electricity generation sub-sectors would change from CAD [161.98, 322.84], [718.97, 2253.75] to [166.55, 332.00], [752.00, 2297.05] $\times 10^8$, respectively. Among them, electricity would be the most sensitive in terms of responding to climate change impacts, representing 4.60 and 1.92% increments under lower and upper bounds. This corresponds to 2.32 and 1.43% increments under the lower and upper bounds of the total system cost. As for the industrial and transportation sub-sectors, there would be no visible impacts that could be identified due to climate change. Thus, there would be no major adaptation schemes to the impacts in these two sub-sectors.

Table 1
Energy related expenditures under BAU case and climate change.

10^8 CAD		C1	C2	C3	C4	C5	Total
BAU	L	215.19	161.98	595.92	229.08	718.97	1921.13
	U	428.97	322.84	1187.79	456.47	2253.75	4649.82
CC	L	222.15	166.55	595.90	229.10	752.00	1965.70
	U	442.80	332.00	1187.80	456.45	2297.05	4716.10

Note: BAU, business as usual; CC, climate change.

Table 2
Facility capacity expansion options under BAU and climate change (over periods 1–5).

	Period	Hydropower	Thermal-NGA	Thermal-coal	Thermal-diesel	Wind
BAU	1	[0,1]	[0,1]	[0,1]	[0,1]	[0,1]
	2	0	0	0	0	1
	3	0	0	0	0	0
	4	1	0	0	0	0
	5	0	0	0	0	0
CC	1	[0,1]	[0,1]	[0,1]	[0,1]	[0,1]
	2	0	0	0	0	1
	3	1	0	0	0	0
	4	0	0	0	0	0
	5	0	0	0	0	0

Note: BAU, business as usual; CC, climate change.

Consumption of many energy resources would be slightly different than those under the BAU case, particularly for those resources that would be mainly consumed in residential, commercial and transportation sectors. For example, under the BAU case, expansion patterns of the electricity generation facilities (including hydropower, natural-gas-, coal-, and diesel-based thermal) would be [0,1] and 1 in periods 1 and 4 for hydropower, and [0,1] in period 1 for natural gas, coal, and diesel based thermal plants (Table 2). For the facilities based on wind energy, the expansion options would be [0,1] and 1 in periods 1 and 2, respectively. However, for most of the facilities, the amounts and patterns of electricity to be produced would be quite similar. This is due to (a) the stability of end-user electricity demands under the BAU case and the changing climatic conditions, representing a slight difference between energy allocation patterns under the two cases, (b) the impacts of climate change, which would be normally limited to the operational activities of relevant facilities based on renewable energy resources such as hydropower and wind, which would be greatly dependent on climatic conditions including humidity, precipitation and wind speed, and (c) the fact that there would be flexibility in the capacity expansion options of relevant electricity generation facilities that might mitigate the impacts of climate change in the power generation sector of Manitoba.

Similarly, the importation of natural gas, fuel oil, LPG and heating oil would be adjusted to a certain degree as adaptation measures for Manitoba's energy sector to the integrated impacts of climate change (Table 3). In detail, importation amounts of the adopted energy resources would be increase slightly. This is mainly because of the responses to the increase in end-user demand. For example, the importation of natural gas would be [432.60, 610.65] and [442.65, 624.90] PJ under the BAU case and the climate change case, respectively. Over periods 2–5, the importation of this energy would be [415.05, 585.95], [383.65, 541.60], [365.70, 516.30], and [359.35, 507.25] PJ under the BAU case, respectively. These amounts would correspondingly increase to [424.85, 599.85], [393.30, 555.25], [374.75, 529.00], and [368.45, 520.10] PJ under climate change impacts, respectively (Fig. 10). In the same period, the importation of fuel oil would increase slightly due to its comparatively small share in the residential and commercial sectors. In detail, over the planning horizon, [165.00, 232.85], [148.80, 210.10], [148.80, 210.10], [140.00, 197.70], and [136.45, 192.55] PJ of fuel oil would be imported under the BAU case, respectively.

Comparatively, due to the impacts of climate change (such as end-user demand growth and electricity production fluctuation), the consumption of fuel oil would increase correspondingly. Over the same period, the amounts would be [166.60, 235.15], [150.45, 212.40], [149.90, 211.60], [141.10, 199.25], and [137.55, 194.10] PJ, respectively (Fig. 11). As for LPG, the importation amounts would change from [29.85, 42.15], [26.80, 37.80], [40.80, 57.60], [40.95, 57.90], and [50.55, 71.35] PJ under the BAU case to [30.05, 42.45], [26.95, 38.05], [40.95, 57.80], [41.15, 58.10], and [50.70, 71.55] PJ under climate change, respectively (Fig. 12). Under the BAU case and climate change, heating oil would account for a small share of the total energy consumption in the province. Specifically, in periods 1–5, [1.00, 1.41], [1.06, 1.49], [1.25, 1.76], [1.31, 1.85], and [1.35, 1.91] PJ of heating oil would be imported under the BAU case, respectively. These amounts would change to [1.03, 1.45], [1.09, 1.54], [1.28, 1.81], [1.34, 1.90], and [1.39, 1.96] PJ, respectively. Such amounts of heating oil would be consumed mainly in residential and commercial sectors of the province, particularly for commercial and residential space and water heating (Fig. 13).

Electricity exportation would be influenced by climate change to a certain degree. Generally, a lesser amount of electricity would be exported from the province than under the BAU case. This is due to the growth of end-user demands for electricity and the reduction of renewable availabilities for electricity production under climate change within the province. For instance, in period 1, [318.10, 449.15] PJ of electricity would be exported from Manitoba (particularly to the US, Ontario and Saskatchewan). This amount would decrease by [8.50, 12.05] to [309.60, 437.10] PJ in the same period under climate change. In the next four periods, electricity exports would change from [380.05, 536.55], [384.10, 542.30], [462.35,

Table 3
Energy importation under BAU case and climate change (over periods 1–5).

Unit: PJ	Period	BAU	CC
NGA	1	[432.60, 610.65]	[442.65, 624.90]
	2	[415.05, 585.95]	[424.85, 599.85]
	3	[383.65, 541.60]	[393.30, 555.25]
	4	[365.70, 516.30]	[374.75, 529.00]
	5	[359.35, 507.25]	[368.45, 520.10]
FO	1	[165.00, 232.85]	[166.60, 235.15]
	2	[148.80, 210.10]	[150.45, 212.40]
	3	[148.80, 210.10]	[149.90, 211.60]
	4	[140.00, 197.70]	[141.10, 199.25]
	5	[136.45, 192.55]	[137.55, 194.10]
LPG	1	[29.85, 42.15]	[30.05, 42.45]
	2	[26.80, 37.80]	[26.95, 38.05]
	3	[40.80, 57.60]	[40.95, 57.80]
	4	[40.95, 57.90]	[41.15, 58.10]
	5	[50.55, 71.35]	[50.70, 71.55]
HO	1	[5.00, 7.05]	[5.15, 7.25]
	2	[5.30, 7.45]	[5.45, 7.70]
	3	[6.25, 8.80]	[6.40, 9.05]
	4	[6.55, 9.25]	[6.70, 9.50]
	5	[6.75, 9.55]	[6.95, 9.80]
ELE EXP	1	[318.10, 449.15]	[309.60, 437.10]
	2	[380.05, 536.55]	[371.60, 524.60]
	3	[384.10, 542.30]	[375.00, 529.45]
	4	[462.35, 652.80]	[452.85, 639.35]
	5	[473.05, 667.85]	[463.90, 654.90]

Note: NGA, natural gas; FO, fuel oil; LPG, liquefied petroleum gas; HO, heating oil; ELE EXP, electricity export; BAU, business as usual; CC, climate change.

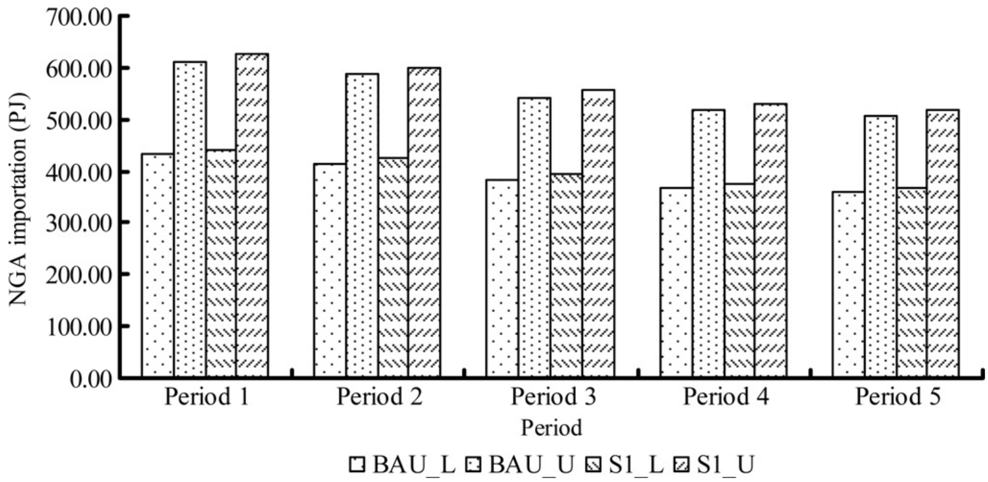

Fig. 10. NGA importation under BAU case and climate change.

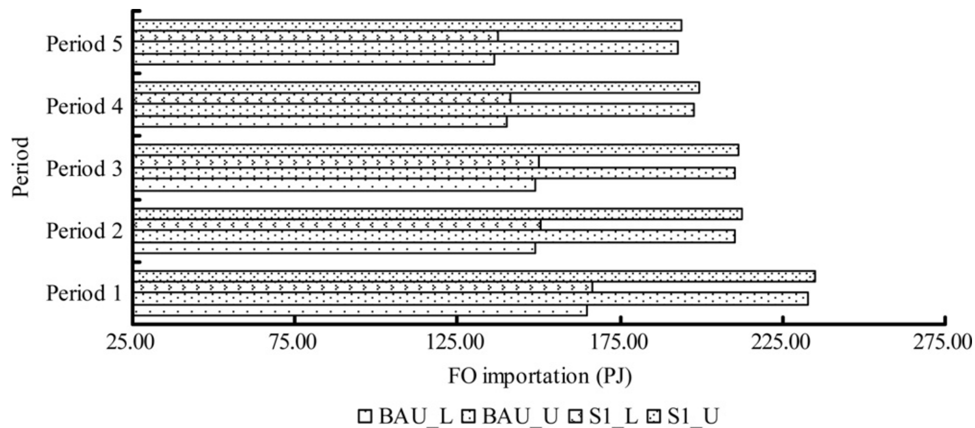

Fig. 11. FO importation under BAU case and climate change.

652.80], and [473.05, 667.85]–PJ under the BAU case to [371.60, 524.60], [375.00, 529.45], [452.85, 639.35], and [463.90, 654.90] PJ under climate change, respectively (Fig. 14).

3.2.2. Residential sub-sector

Mostly, in the two sub-sectors (i.e., residential and commercial) of Manitoba's energy sector, allocation patterns of many energy resources would change slightly under climate change and the BAU case (Figs. 15 and 16, Tables 4–13). In the residential sub-sector, natural gas would still be the primary energy contributor. In detail, over periods 1–5, natural gas allocation would increase to a certain degree from [184.06, 259.83], [174.66, 246.60], [166.76, 235.45], [160.33, 226.36], and [151.68, 214.14] PJ under the BAU

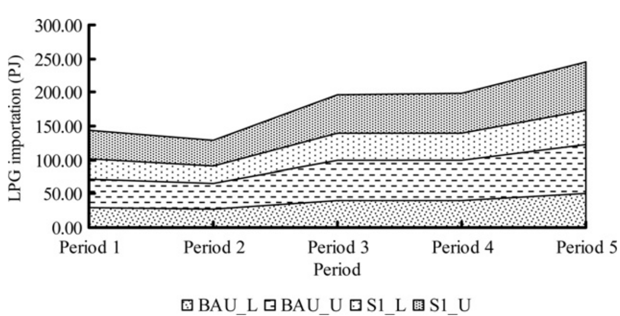

Fig. 12. LPG importation under BAU case and climate change.

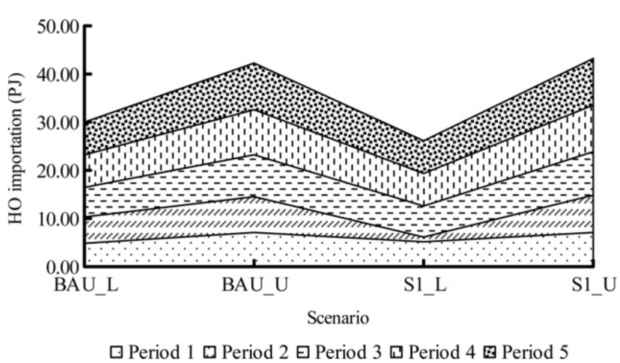

Fig. 13. HO importation under BAU case and climate change.

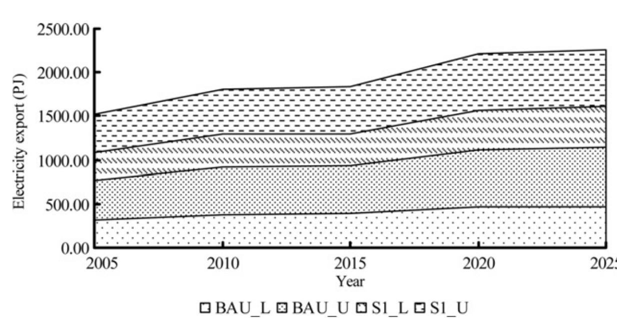

Fig. 14. Electricity export under BAU case and climate change.

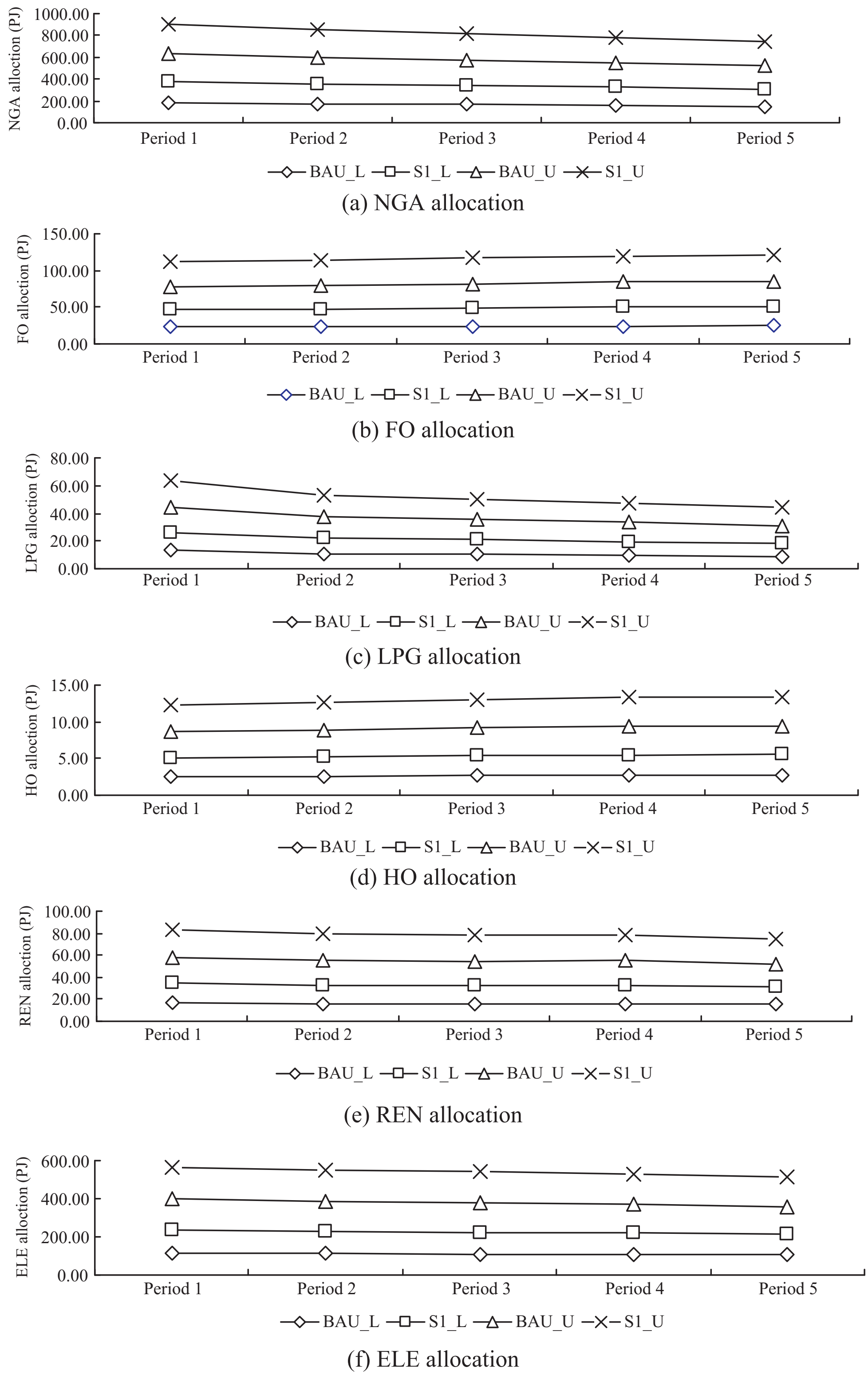

Fig. 15. Energy allocation to residential sub-sector under BAU case and climate change.

case to [189.82, 267.97], [180.12, 254.30], [171.94, 242.77], [165.32, 233.40], and [156.40, 220.81] PJ under climate change, respectively. As for fuel oil, the allocations to the residential sector would be [22.66, 31.98], [23.18, 32.73], [23.67, 33.43], [24.37, 34.40], and [24.53, 34.63] PJ over periods 1–5 under the BAU case, respectively. At the same time, the allocations under climate change would be [23.60, 33.32], [24.15, 34.09], [24.66, 34.82], [25.38, 35.83], and [25.55, 36.08] PJ, respectively. In terms of LPG, [13.16, 18.61] and [13.02, 18.40] PJ would be allocated to the residential sub-sector in period 1 under climate change and the BAU case, respectively. In period 2, these two amounts would change to [11.11, 15.69] and [11.02, 15.56] PJ, respectively. Over the next 3 periods, [10.40, 14.68], [9.80, 13.84] and [9.12, 12.88] PJ of LPG would be allocated to the residential sub-sector under the BAU case. Over the

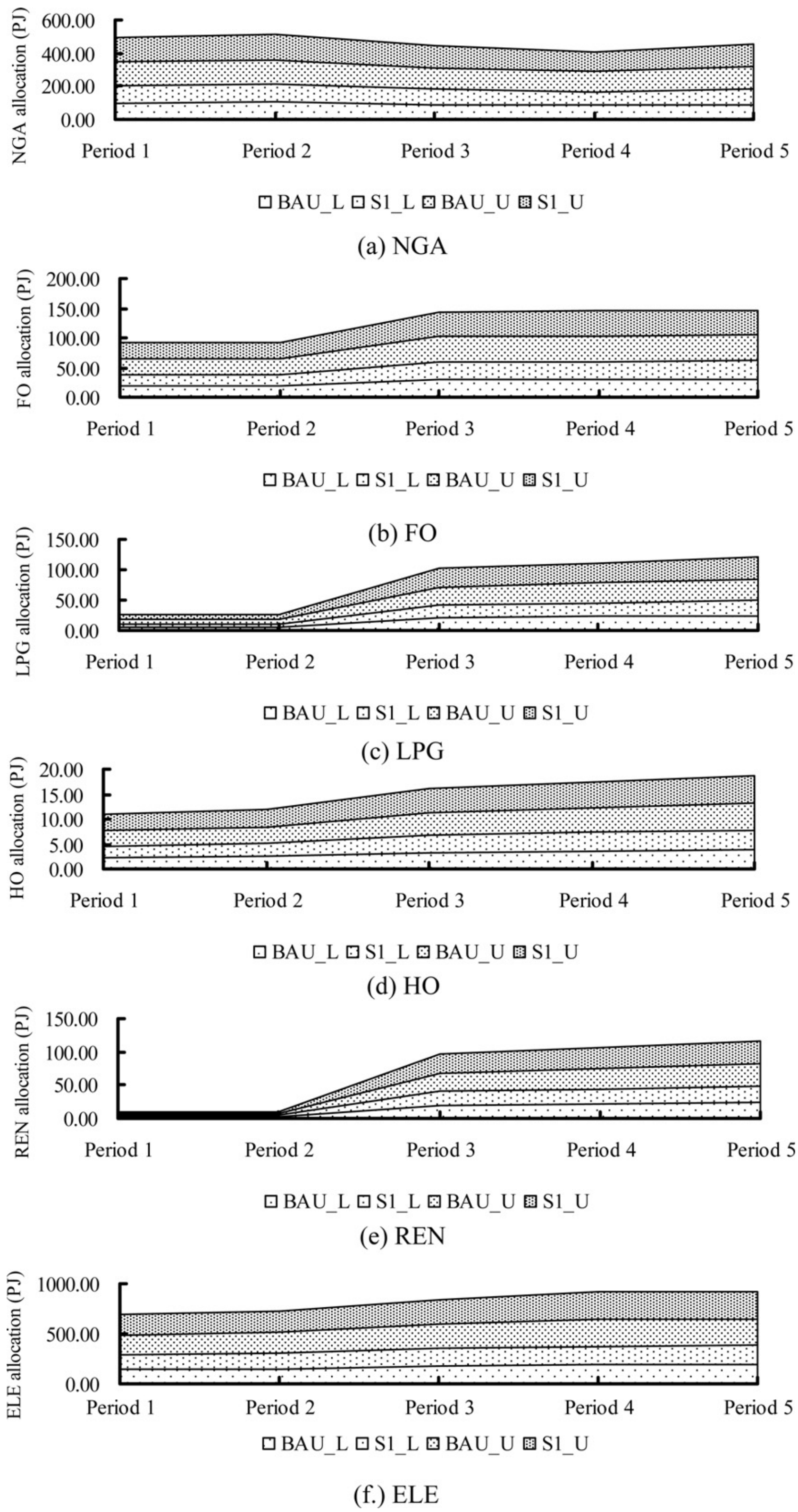

Fig. 16. Energy allocation in the commercial sub-sector under BAU case and climate change.

same period, these amounts would increase to [10.48, 14.79], [9.88, 13.95], and [9.19, 12.98] PJ under climate change, respectively. Moreover, a small portion of heating oil would be allocated to the residential sub-sector in the province. In period 1, [2.53, 3.58] and [2.59, 3.66] PJ of heating oil would be allocated to relevant end-demands in this sub-sector under the BAU case and climate change, respectively. Over periods 2–5, the consumption of heating oil would increase gradually. In these periods, [2.59, 3.66], [2.66, 3.75], [2.72, 3.85], and [2.74, 3.86] PJ of heating oil would be allocated to the residential sub-sector under the BAU case, respectively. In order to meet increasing end-user demands due to climate change, the allocation of heating oil would increase slightly in peri-

Table 4
Energy allocation to residential sub-sector under climate change (period 1).

	Energy resource	End-user sub-sector	BAU	CC
X1111	NGA	Space heating	[24.54, 34.64]	[25.64, 36.20]
X1141		Water heating	[10.73, 15.14]	[10.73, 15.14]
X1151		Lighting	[0.23, 0.32]	[0.23, 0.32]
X1161		Appliances and others	[1.32, 1.87]	[1.37, 1.94]
X1211	FO	Space heating	[4.21, 5.94]	[4.40, 6.21]
X1231		Space cooling	0	0
X1241		Water heating	[0.33, 0.46]	[0.33, 0.46]
X1311	LPG	Space heating	[0.42, 0.59]	[0.44, 0.62]
X1331		Space cooling	[0.23, 0.33]	[0.24, 0.35]
X1341		Water heating	[1.95, 2.75]	[1.95, 2.75]
X1351		Lighting	0	0
X1361		Appliances and others	0	0
X1411	HO	Space heating	[0.26, 0.37]	[0.27, 0.39]
X1441		Water heating	[0.24, 0.34]	[0.24, 0.34]
X1511	REN	Space heating	[1.05, 1.48]	[1.10, 1.55]
X1541		Water heating	[0.98, 1.38]	[0.98, 1.38]
X1561		Appliances and others	[1.34, 1.89]	[1.45, 2.04]
X1611	ELE	Space heating	[8.41, 11.88]	[8.79, 12.41]
X1631		Space cooling	[0.33, 0.47]	[0.34, 0.49]
X1641		Water heating	[1.95, 2.75]	[1.95, 2.75]
X1651		Lighting	[2.43, 3.42]	[2.43, 3.42]
X1661		Appliances and others	[9.95, 14.04]	[10.39, 14.67]

Note: NGA, natural gas; FO, fuel oil; LPG, liquefied petroleum gas; HO, heating oil; REN, renewable energy and wood waste; ELE, electricity.

ods 2–5 ([2.65, 3.74], [2.72, 3.84], [2.79, 3.94] and [2.80, 3.95] PJ in periods 2–5, respectively). Under the integrated impacts of climate change, the allocation of renewable energy resources would increase to a certain degree compared to those under the BAU case. For instance, in periods 1–5, [16.85, 23.75], [16.05, 22.70], [15.80, 22.30], [15.95, 22.50], and [15.15, 21.40] PJ of renewable energy resources would be allocated to various end-users in the residential sub-sector under the BAU case, respectively. At the same time, [17.61, 24.82], [16.77, 23.72], [16.51, 23.30], [16.67, 23.51], and [15.83, 22.36] PJ of the same energy resources would be allocated to the same sub-sector under climate change, respectively. Furthermore, as the second major resource in the residential sub-sector, electricity consumption would change to a certain degree under the two cases (i.e., BAU and climate change). In period 1, [115.32, 162.80] and [119.52, 168.73] PJ of electricity would be allocated to the residential sub-sector under the BAU case and climate change, respectively. Over the rest of the four periods, [112.47, 158.81], [109.94, 155.26], [107.64, 151.97], and [104.23, 147.15] PJ of electricity would be allocated to this sub-sector under the BAU case, respectively. Over the same four periods, the amount of electric-

Table 5
Energy allocation to residential sub-sector under climate change (period 2).

	Energy resource	End-user sub-sector	BAU	CC
X1112	NGA	Space heating	[23.18, 32.72]	[24.22, 34.19]
X1142		Water heating	[10.24, 14.46]	[10.24, 14.46]
X1152		Lighting	[0.23, 0.32]	[0.23, 0.33]
X1162		Appliances and others	[1.29, 1.82]	[1.34, 1.89]
X1212	FO	Space heating	[4.30, 6.08]	[4.50, 6.35]
X1232		Space cooling	0	0
X1242		Water heating	[0.33, 0.47]	[0.33, 0.47]
X1312	LPG	Space heating	[0.39, 0.55]	[0.41, 0.58]
X1332		Space cooling	0	0
X1342		Water heating	[1.81, 2.56]	[1.81, 2.56]
X1352		Lighting	0	0
X1362		Appliances and others	0	0
X1412	HO	Space heating	[0.27, 0.38]	[0.28, 0.40]
X1442		Water heating	[0.25, 0.35]	[0.25, 0.35]
X1512	REN	Space heating	[1.08, 1.52]	[1.12, 1.59]
X1522		Wood heating	0	0
X1542		Water heating	[1.00, 1.41]	[1.00, 1.41]
X1562		Appliances and others	[1.14, 1.61]	[1.23, 1.75]
X1612	ELE	Space heating	[7.83, 11.05]	[8.18, 11.54]
X1632		Space cooling	[0.57, 0.80]	[0.60, 0.84]
X1642		Water heating	[1.81, 2.56]	[1.81, 2.56]
X1652		Lighting	[2.66, 3.76]	[2.66, 3.76]
X1662		Appliances and others	[9.62, 13.60]	[10.06, 14.21]

Note: NGA, natural gas; FO, fuel oil; LPG, liquefied petroleum gas; HO, heating oil; REN, renewable energy and wood waste; ELE, electricity.

Table 6
Energy allocation to residential sub-sector under climate change (period 3).

	Energy resource	End-user sub-sector	BAU	CC
X1113	NGA	Space heating	[21.96, 31.01]	[22.95, 32.41]
X1143		Water heating	[9.89, 13.97]	[9.89, 13.97]
X1153		Lighting	[0.22, 0.32]	[0.22, 0.32]
X1163		Appliances and others	[1.27, 1.80]	[1.32, 1.87]
X1213	FO	Space heating	[4.39, 6.20]	[4.59, 6.48]
X1233		Space cooling	0	0
X1243		Water heating	[0.34, 0.48]	[0.34, 0.48]
X1313	LPG	Space heating	[0.37, 0.52]	[0.38, 0.54]
X1333		Space cooling	0	0
X1343		Water heating	[1.71, 2.42]	[1.71, 2.42]
X1353		Lighting	0	0
X1363		Appliances and others	0	0
X1413	HO	Space heating	[0.27, 0.39]	[0.29, 0.41]
X1443		Water heating	[0.26, 0.36]	[0.26, 0.36]
X1513	REN	Space heating	[1.10, 1.55]	[1.15, 1.62]
X1523		Wood heating	0	0
X1543		Water heating	[1.03, 1.45]	[1.03, 1.45]
X1563		Appliances and others	[1.03, 1.46]	[1.13, 1.59]
X1613	ELE	Space heating	[7.32, 10.34]	[7.65, 10.80]
X1633		Space cooling	[0.60, 0.85]	[0.63, 0.89]
X1643		Water heating	[1.71, 2.42]	[1.71, 2.42]
X1653		Lighting	[2.84, 4.01]	[2.84, 4.01]
X1663		Appliances and others	[9.51, 13.44]	[9.94, 14.04]

Note: NGA, natural gas; FO, fuel oil; LPG, liquefied petroleum gas; HO, heating oil; REN, renewable energy and wood waste; ELE, electricity.

ity that would be allocated to the same sector would be [116.53, 164.53], [113.86, 160.80], [111.48, 157.39], and [107.94, 152.40] PJ under climate change, respectively.

3.2.3. *Commercial sub-sector*

In the commercial sub-sector, climate change would have similar effects on energy allocation patterns (Fig. 16). In terms of natural gas, [100.83, 142.34] and [104.64, 147.72] PJ would be allocated to this sub-sector in period 1 under the BAU case and the climate-change case, respectively. Over periods 2–5, energy allocations to the sub-sector would be [104.04, 146.91], [90.51, 127.75], [82.72, 116.78], and [91.54, 129.22] PJ under the BAU case. Due to the impacts of climate change, these amounts would increase to [107.96, 152.44], [94.58, 133.50], [86.45, 122.03], and [95.66, 135.04] PJ, respectively. These increments would be mainly caused by the increase of end-user demands as adaptation schemes to climate change impacts and the replacement of technologies induced by technological efficiency upgrades. Over the planning horizon (periods 1–5), the allocations of fuel oil would be [18.79, 26.52], [18.85, 26.62], [29.81, 42.08], [29.96, 42.32], and [30.53, 43.10] PJ under the BAU case, respectively. Comparatively, under the impacts of climate change, the allocations of fuel oil would be [19.37, 27.34], [19.44, 27.44], [29.85, 42.13], [30.00, 42.36], and [30.56, 43.10] PJ over periods 1–5, respectively. In terms of LPG, the allocations

Table 7
Energy allocation to residential sub-sector under climate change (period 4).

	Energy resource	End-user sub-sector	BAU	CC
X1114	NGA	Space heating	[21.11, 29.80]	[22.06, 31.14]
X1144		Water heating	[9.49, 13.41]	[9.49, 13.41]
X1154		Lighting	[0.22, 0.30]	[0.22, 0.30]
X1164		Appliances and others	[1.25, 1.76]	[1.29, 1.83]
X1214	FO	Space heating	[4.52, 6.39]	[4.73, 6.67]
X1234		Space cooling	0	0
X1244		Water heating	[0.35, 0.49]	[0.35, 0.49]
X1314	LPG	Space heating	[0.35, 0.49]	[0.36, 0.51]
X1334		Space cooling	0	0
X1344		Water heating	[1.61, 2.28]	[1.61, 2.28]
X1354		Lighting	0	0
X1364		Appliances and others	0	0
X1414	HO	Space heating	[0.28, 0.40]	[0.30, 0.42]
X1444		Water heating	[0.26, 0.37]	[0.26, 0.37]
X1514	REN	Space heating	[1.13, 1.60]	[1.18, 1.67]
X1524		Wood heating	0	0
X1544		Water heating	[1.05, 1.48]	[1.05, 1.48]
X1564		Appliances and others	[1.01, 1.42]	[1.10, 1.55]
X1614	ELE	Space heating	[6.96, 9.82]	[7.27, 10.27]
X1634		Space cooling	[0.68, 0.96]	[0.71, 1.01]
X1644		Water heating	[1.50, 2.11]	[1.50, 2.11]
X1654		Lighting	[2.96, 4.17]	[2.96, 4.17]
X1664		Appliances and others	[9.43, 13.32]	[9.86, 13.92]

Note: NGA, natural gas; FO, fuel oil; LPG, liquefied petroleum gas; HO, heating oil; REN, renewable energy and wood waste; ELE, electricity.

Table 8
Energy allocation to residential sub-sector under climate change (period 5).

	Energy resource	End-user sub-sector	BAU	CC
X1115	NGA	Space heating	[19.93, 28.14]	[20.83, 29.41]
X1145		Water heating	[8.97, 12.67]	[8.97, 12.67]
X1155		Lighting	[0.20, 0.28]	[0.20, 0.28]
X1165		Appliances and others	[1.23, 1.74]	[1.28, 1.81]
X1215	FO	Space heating	[4.56, 6.43]	[4.76, 6.72]
X1235		Space cooling	0	0
X1245		Water heating	[0.35, 0.49]	[0.35, 0.49]
X1315	LPG	Space heating	[0.33, 0.46]	[0.34, 0.48]
X1335		Space cooling	0	0
X1345		Water heating	[1.50, 2.12]	[1.50, 2.12]
X1355		Lighting	0	0
X1365		Appliances and others	0	0
X1415	HO	Space heating	[0.28, 0.40]	[0.30, 0.42]
X1445		Water heating	[0.26, 0.37]	[0.26, 0.37]
X1515	REN	Space heating	[1.14, 1.61]	[1.19, 1.68]
X1525		Wood heating	0	0
X1545		Water heating	[1.05, 1.48]	[1.05, 1.48]
X1565		Appliances and others	[0.84, 1.19]	[0.93, 1.31]
X1615	ELE	Space heating	[6.51, 9.19]	[6.80, 9.60]
X1635		Space cooling	[0.76, 1.07]	[0.79, 1.11]
X1645		Water heating	[1.40, 1.97]	[1.40, 1.97]
X1655		Lighting	[2.92, 4.13]	[2.92, 4.13]
X1665		Appliances and others	[9.26, 13.07]	[9.68, 13.66]

Note: NGA, natural gas; FO, fuel oil; LPG, liquefied petroleum gas; HO, heating oil; REN, renewable energy and wood waste; ELE, electricity.

would be [5.21, 7.35] and [5.26, 7.43] PJ in period 1 under the BAU case and climate change, respectively. Over the rest of the four periods, the allocations of LPG would increase gradually. For instance, the amounts of LPG over periods 2–5 would be [5.69, 8.04], [21.03, 29.68], [22.79, 32.19], and [24.97, 35.21] PJ under the BAU case, respectively. Comparatively, under climate change, these amounts would change to [5.75, 8.12], [21.09, 29.77], [22.85, 32.28], and [25.03, 35.30] PJ, respectively. The sharp increase of LPG consumption after period 3 is mainly due to the increase of efficiencies associated with technologies based on LPG as well as the interventions of governmental polices. As for fuel oil, the allocation amounts would be [2.22, 3.13], [2.45, 3.47], [3.32, 4.68], [3.58, 5.06], and [3.82, 5.39] PJ under the BAU case over periods 1–5, respectively. On the other hand, these amounts would change to [2.30, 3.25], [2.55, 3.60], [3.42, 4.83], [3.70, 5.22], and [3.94, 5.56] PJ under climate change, respectively. Also, renewable energy would account for an increasing share among energy consumption in the commercial sector of the province. Under the two scenarios, [1.96, 2.76] and [1.97, 2.79] PJ of renewable energies would be allocated to the commercial sun-sector in period 1, respectively. Over the next four periods, [2.18, 3.08], [20.17, 28.46], [21.95, 31.01], and [24.18, 34.10] PJ under the BAU case. These would be change to [2.20, 3.11], [20.19, 28.49], [21.97, 31.04], and [25.20, 34.13] PJ under climate change, respectively. Obviously, electricity would be the

Table 9
Energy allocation to commercial sub-sector under climate change (period 1).

	Energy resource	End-user sub-sector	BAU	CC
X2111	NGA	Space heating	[15.21, 21.47]	[15.89, 22.44]
X2131		Water heating	[3.23, 4.57]	[3.23, 4.57]
X2161		Appliances and others	[1.72, 2.43]	[1.80, 2.54]
X2211	FO	Space heating	[2.57, 3.63]	[2.69, 3.79]
X2231		Water heating	[0.06, 0.08]	[0.06, 0.08]
X2241		Ventilation	[1.13, 1.60]	[1.13, 1.60]
X2261		Appliances and others	0	0
X2311	LPG	Space heating	[0.25, 0.36]	[0.26, 0.37]
X2331		Water heating	[0.79, 1.11]	[0.79, 1.11]
X2351		Lighting	0	0
X2361		Appliances and others	0	0
X2411	HO	Space heating	[0.38, 0.54]	[0.40, 0.56]
X2431		Water heating	[0.06, 0.09]	[0.06, 0.09]
X2511	REN	Space heating	[0.08, 0.12]	[0.08, 0.11]
X2531		Water heating	[0.315, 0.45]	[0.32, 0.45]
X2561		Appliances and others	0	0
X2611	ELE	Space heating	[6.08, 8.59]	[6.36, 8.97]
X2621		Space cooling	[2.81, 3.97]	[2.94, 4.15]
X2631		Water heating	[0.53, 0.74]	[0.53, 0.74]
X2641		Ventilation	[2.42, 3.42]	[2.42, 3.42]
X2651		Lighting	[6.07, 8.58]	[6.07, 8.58]
X2661		Appliances and others	[10.34, 14.58]	[10.80, 15.24]

Note: NGA, natural gas; FO, fuel oil; LPG, liquefied petroleum gas; HO, heating oil; REN, renewable energy and wood waste; ELE, electricity.

Table 10
Energy allocation to commercial sub-sector under climate change (period 2).

	Energy resource	End-user sub-sector	BAU	CC
X2112	NGA	Space heating	[15.70, 22.17]	[16.41, 23.16]
X2132		Water heating	[3.39, 4.78]	[3.39, 4.78]
X2162		Appliances and others	[1.72, 2.43]	[1.80, 2.54]
X2212	FO	Space heating	[2.60, 3.67]	[2.71, 3.83]
X2232		Water heating	[0.06, 0.08]	[0.06, 0.08]
X2242		Ventilation	[1.11, 1.57]	[1.11, 1.57]
X2262		Appliances and others	0	0
X2312	LPG	Space heating	[0.26, 0.37]	[0.27, 0.38]
X2332		Water heating	[0.88, 1.24]	[0.88, 1.24]
X2352		Lighting	0	0
X2362		Appliances and others	0	0
X2412	HO	Space heating	[0.42, 0.59]	[0.44, 0.62]
X2432		Water heating	[0.07, 0.10]	[0.07, 0.10]
X2512	REN	Space heating	[0.08, 0.12]	[0.09, 0.12]
X2532		Water heating	[0.35, 0.50]	[0.35, 0.50]
X2562		Appliances and others	0	0
X2612	ELE	Space heating	[6.12, 8.64]	[6.39, 9.03]
X2622		Space cooling	[2.87, 4.05]	[3.00, 4.24]
X2632		Water heating	[0.54, 0.76]	[0.54, 0.76]
X2642		Ventilation	[2.45, 3.46]	[2.45, 3.46]
X2652		Lighting	[7.07, 9.98]	[7.07, 9.98]
X2662		Appliances and others	[10.73, 15.15]	[11.21, 15.83]

Note: NGA, natural gas; FO, fuel oil; LPG, liquefied petroleum gas; HO, heating oil; REN, renewable energy and wood waste; ELE, electricity.

largest energy contributor in the commercial sub-sector. In period 1, [141.27, 199.39] and [145.59, 205.50] PJ would be allocated to the sector under the BAU case and the climate change scenario. Over periods 2–5, the allocations of electricity would be [148.90, 210.20], [171.35, 241.88], [186.41, 263.07], and [187.23, 264.31] PJ under the BAU case, respectively. Comparatively, these amounts would increase to [153.33, 216.47], [176.53, 249.19], [192.08, 271.07], and [192.68, 272.00] PJ under climate change, respectively.

3.2.4. *Transportational sub-sector*

The end-users of the transportation sub-sector in Manitoba include light-duty vehicles, freight trucks, buses, air planes, recreational vehicles and the railway. In this research, an assumption is assigned that climate change would not have significantly direct impacts on this sub-sector. According to the results, the energy consumption structure of the transportation sector would be greatly different from those of the commercial and residential ones. In this sector, the primary energy resources would be RPPs such as diesel, gasoline, LPG, and jet fuel. Among them, gasoline and diesel would be the largest two resources (Fig. 17). Overall, the largest contributor to this sector would be gasoline, with a total consumption of [1327.40, 1873.91] PJ over the planning horizon. The second largest one within this sub-sector would be diesel which would be consumed at [982.95, 1387.75] PJ in total. Also, [32.75, 46.25], [14.55, 20.45], [48.65, 68.70], [287.40, 405.80], and [264.50, 373.20] PJ of natural gas, fuel oil, LPG, jet fuel, and

Table 11
Energy allocation to commercial sub-sector under climate change (period 3).

	Energy resource	End-user sub-sector	BAU	CC
X2113	NGA	Space heating	[16.34, 23.06]	[17.07, 24.09]
X2133		Water heating	0	0
X2163		Appliances and others	[1.77, 2.49]	[1.85, 2.61]
X2213	FO	Space heating	[0.16, 0.22]	[0.16, 0.22]
X2233		Water heating	[4.73, 6.67]	[4.73, 6.67]
X2243		Ventilation	[1.08, 1.53]	[1.08, 1.53]
X2263		Appliances and others	0	0
X2313	LPG	Space heating	[0.27, 0.38]	[0.29, 0.39]
X2333		Water heating	[3.94, 5.56]	[3.94, 5.56]
X2353		Lighting	0	0
X2363		Appliances and others	0	0
X2413	HO	Space heating	[0.47, 0.66]	[0.49, 0.69]
X2433		Water heating	[0.20, 0.28]	[0.20, 0.28]
X2513	REN	Space heating	[0.09, 0.13]	[0.10, 0.14]
X2533		Water heating	[3.94, 5.56]	[3.94, 5.56]
X2563		Appliances and others	0	0
X2613	ELE	Space heating	[8.71, 12.29]	[9.10, 12.85]
X2623		Space cooling	[2.94, 4.14]	[3.07, 4.32]
X2633		Water heating	[0.79, 1.11]	[0.79, 1.11]
X2643		Ventilation	[2.43, 3.43]	[2.43, 3.43]
X2653		Lighting	[8.05, 11.37]	[8.05, 11.37]
X2663		Appliances and others	[11.35, 16.03]	[11.86, 16.75]

Note: NGA, natural gas; FO, fuel oil; LPG, liquefied petroleum gas; HO, heating oil; REN, renewable energy and wood waste; ELE, electricity.

Table 12
Energy allocation to commercial sub-sector under climate change (period 4).

	Energy resource	End-user sub-sector	BAU	CC
X2114	NGA	Space heating	[16.54, 23.36]	[17.29, 24.41]
X2134		Water heating	0	0
X2164		Appliances and others	0	0
X2214	FO	Space heating	[0.15, 0.22]	[0.16, 0.22]
X2234		Water heating	[4.78, 6.75]	[4.78, 6.75]
X2244		Ventilation	[1.06, 1.49]	[1.06, 1.49]
X2264		Appliances and others	0	0
X2314	LPG	Space heating	[0.27, 0.38]	[0.28, 0.40]
X2334		Water heating	[4.29, 6.06]	[4.29, 6.06]
X2354		Lighting	0	0
X2364		Appliances and others	0	0
X2414	HO	Space heating	[0.50, 0.71]	[0.52, 0.74]
X2434		Water heating	[0.21, 0.30]	[0.21, 0.30]
X2514	REN	Space heating	[0.10, 0.14]	[0.10, 0.15]
X2534		Water heating	[4.29, 6.06]	[4.29, 6.06]
X2564		Appliances and others	0	0
X2614	ELE	Space heating	[8.65, 12.21]	[9.04, 12.76]
X2624		Space cooling	[3.00, 4.24]	[3.14, 4.43]
X2634		Water heating	[0.78, 1.10]	[0.78, 1.10]
X2644		Ventilation	[2.43, 3.42]	[2.43, 3.42]
X2654		Lighting	[8.86, 12.51]	[8.86,12.51]
X2664		Appliances and others	[13.56, 19.13]	[14.17, 19.99]

Note: NGA, natural gas; FO, fuel oil; LPG, liquefied petroleum gas; HO, heating oil; REN, renewable energy and wood waste; ELE, electricity.

electricity would be utilized over the planning horizon, respectively.

In detail, in period 1, [7.35, 10.40] PJ of natural gas would be adopted for buses in this sub-sector. Fuel oil would be only scarcely used for transportation activities, with only [2.55, 3.55] PJ being consumed for lubricants. At the same time, [6.45, 9.10] and [3.70, 5.20] PJ of LPG would be used for light-duty vehicles and buses, respectively. As one of the major two resources in the transportation sub-sector, [220.85, 311.75], [15.20, 21.45], [4.40, 5.00], [24.45, 34.60], and [4.00, 5.60] PJ of gasoline would be consumed by light-duty vehicles, freight trucks, buses, recreational activities and rail transportation in period 1, respectively. Similarly, for the adoption of diesel, the amounts would be [69.55, 98.20], [91.10, 128.60], [9.45, 13.35], [10.85, 15.35], and [7.15, 10.10] PJ in the sub-sectors of light-duty vehicles, freight trucks, buses, recreational activities and rail transportation, respectively. Although most of the energy demands in the sub-sector would be satisfied by RPPs, electricity would also make up a certain portion. In period 1, [19.35, 27.30], [3.70, 5.20], [3.45, 4.85], [8.15, 11.55], and [19.10, 26.95] PJ of electricity would be allocated to light-duty vehicles, buses, air planes, recreational activities, and railways transportation, respectively. In periods 2–5, consumption of these energy resources would be varied slightly due to the increase of end-user demands, as well as the variations of utilization efficiencies.

Over the 25-year planning period, several energy resources would be used for light-duty vehicles, including natural gas, LPG,

Table 13
Energy allocation to commercial sub-sector under climate change (period 5).

	Energy resource	End-user sub-sector	BAU	CC
X2115	NGA	Space heating	[16.42, 23.18]	[17.16, 24.22]
X2135		Water heating	0	0
X2165		Appliances and others	[1.89, 2.67]	[1.97, 2.79]
X2215	FO	Space heating	[0.15, 0.21]	[0.16, 0.22]
X2235		Water heating	[4.92, 6.94]	[4.92, 6.94]
X2245		Ventilation	[1.04, 1.46]	[1.04, 1.46]
X2265		Appliances and others	0	0
X2315	LPG	Space heating	[0.26, 0.37]	[0.28, 0.39]
X2335		Water heating	[4.73, 6.67]	[4.73, 6.67]
X2355		Lighting	0	0
X2365		Appliances and others	0	0
X2415	HO	Space heating	[0.53, 0.75]	[0.55, 0.78]
X2435		Water heating	[0.24, 0.33]	[0.24, 0.33]
X2515	REN	Space heating	[0.11, 0.15]	[0.11, 0.16]
X2535		Water heating	[4.73, 6.67]	[4.73, 6.67]
X2565		Appliances and others	0	0
X2615	ELE	Space heating	[8.44, 11.92]	[8.82, 12.45]
X2625		Space cooling	[3.01, 4.26]	[3.15, 4.45]
X2635		Water heating	[0.79, 1.11]	[0.79, 1.11]
X2645		Ventilation	[2.42, 3.41]	[2.42, 3.41]
X2655		Lighting	[10.04, 14.17]	[10.04, 14.17]
X2665		Appliances and others	[12.75, 18.00]	[13.32, 18.81]

Note: NGA, natural gas; FO, fuel oil; LPG, liquefied petroleum gas; HO, heating oil; REN, renewable energy and wood waste; ELE, electricity.

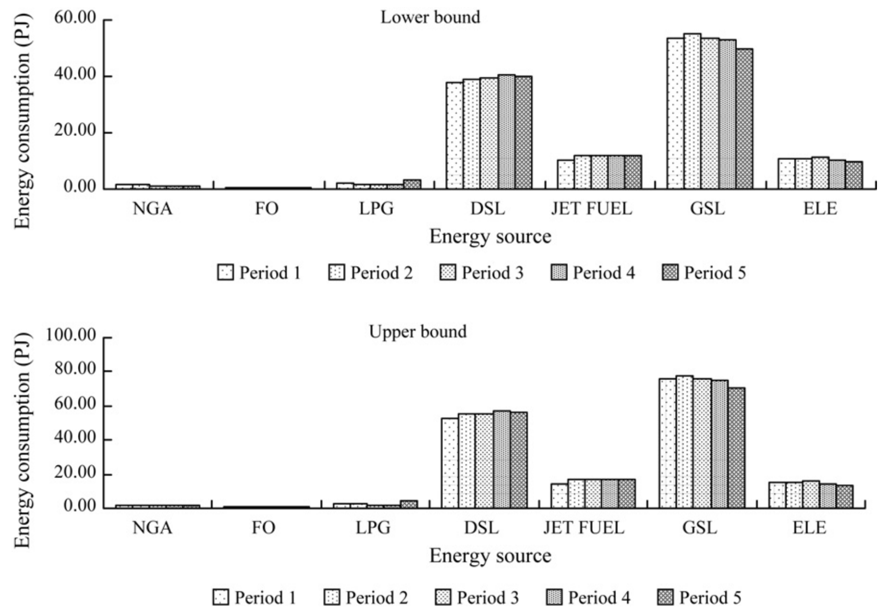

Fig. 17. Energy allocation to the transportation sub-sector over periods 1–5.

diesel, gasoline and electricity. Specifically, 0, [6.45, 9.10], [69.55, 98.20], [220.85, 311.75] and [19.35, 27.30] PJ of those energy resources would be adopted in period 1. For the next four periods, the energy structure of the transportation sub-sector would be mostly stable (Fig. 18). There would be minor increments in electricity due to the upgrade of technologies related to electricity-based vehicles. In contrast, consumption of gasoline and diesel would gradually decrease over the planning horizon. This is due to the improvements of fuel economy, which is associated with relevant vehicles and the gradual improvement in the adoption of those based on electricity and LPG. In detail, over the planning horizon, energy allocated to light-duty vehicles would include [5.35, 7.55], [4.45, 6.30], [3.90, 5.55], and [3.35, 4.75] PJ of LPG, [69.95, 98.80], [66.90, 94.45], [65.10, 91.95], and [60.30, 85.15] PJ of diesel, [228.10, 322.05], [223.05, 314.90], [221.30, 312.45], and [208.45, 294.30] PJ of gasoline, and [21.40, 30.20], [22.30, 31.50], [23.50, 33.20], and [23.45, 33.10] PJ of electricity, respectively.

Similar to the energy consuming patterns of light-duty vehicles, energy resources utilized for freight trucks would include natural gas, LPG, diesel, gasoline and electricity. Among them, diesel and gasoline would be the primary two resources. In periods 1–5, [91.10, 128.60], [101.10, 142.75], [108.85, 153.65], [117.15, 165.35], and [121.20, 171.10] PJ of diesel, and [15.20, 21.45], [16.85, 23.80], [18.15, 25.60], [19.55, 27.55], and [20.20, 28.50] PJ of gasoline would be used (Fig. 19). Minor increments could be identified in the energy consumption associated with freight trucks. This is mainly due to the combined effects of increased end-user demands for freight transport and improved fuel economy in the near future. Although natural gas and LPG might be available for freight trucks, they would not be utilized due to the limited availability of relevant technologies to the public, as well as increased capital and operating costs.

In Manitoba, buses comprise the majority of public transit system vehicles. In this study, technologies based on natural gas, LPG, diesel, gasoline and electricity are considered as the fuels adopted for use by various types of buses. Over the planning horizon, energy consumption for buses is presented in Fig. 20. As the results indicate, diesel would be the primary resource for buses. Accompanied with the improvement of utilization efficiencies, the advancement of relevant technologies, and the restriction of greenhouse gas emissions, the adoption of electricity, LPG, and natural gas would increase slightly over the 25-year period; comparatively, the adop-

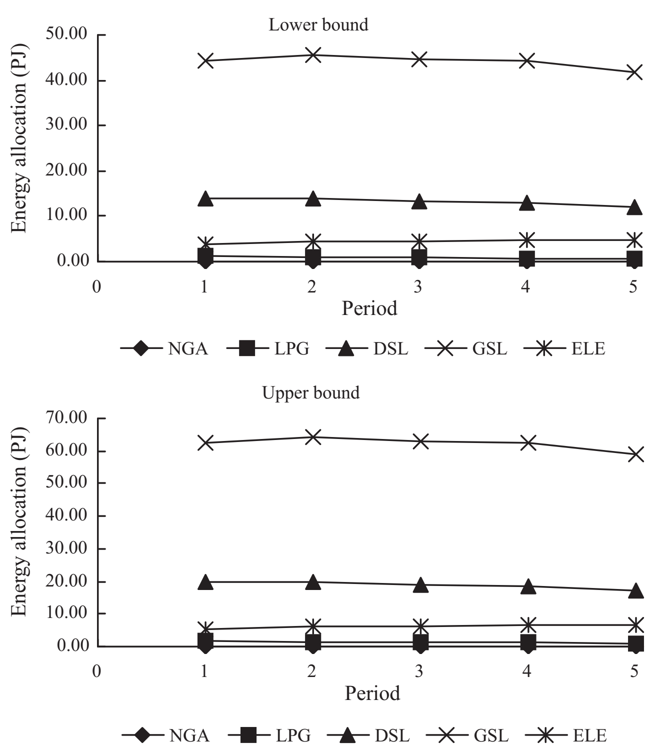

Fig. 18. Energy allocation in light-duty vehicle of transportation sub-sector.

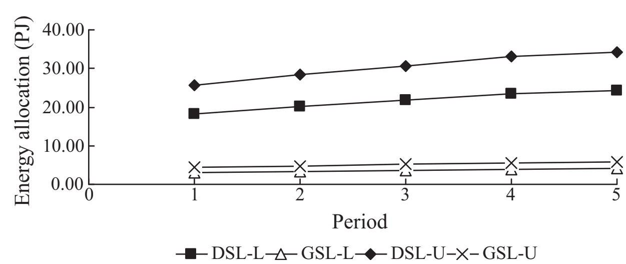

Fig. 19. Energy allocation to freight truck over periods 1–5.

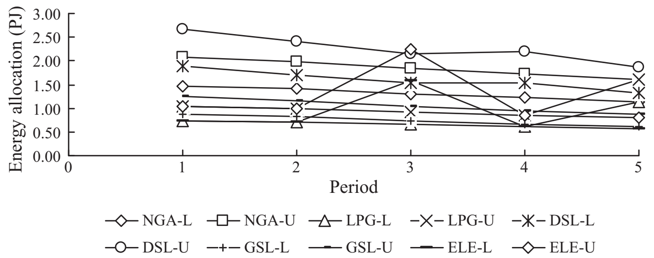

Fig. 20. Energy allocation to buses over the planning horizon.

tion of diesel and gasoline would be relatively stable. Thus, the total amount of energy resources that are allocated to buses would increase slightly, reflecting variations of end-user demands for such resources. In detail, in period 1, [7.35, 10.40], [3.70, 5.20], [9.45, 13.35], [4.40, 6.25], and [3.70, 5.20] PJ of natural gas, LPG, diesel, gasoline and electricity would be allocated to buses, respectively. Over the next three periods, these amounts would change to [7.05, 9.95], [3.50, 4.95], [8.55, 12.05], [4.10, 5.80], and [3.50, 4.95] in period 2, [6.55, 9.25], [3.30, 4.60], [7.65, 10.80], [3.70, 5.25], and [7.95, 11.20] PJ in period 3, [6.10, 8.60], [3.05, 4.30], [7.70, 10.95], [3.35, 4.75], and [3. 05, 4.30] PJ in period 4, and [5.70, 8.05], [5.70, 8.05], [6.65, 9.35], [3.10, 4.35], and [2.85, 4.05] PJ in period 5, respectively.

There would be a large amount of energy allocated to airplanes in the province. In detail, [51.25, 72.35], [59.05, 83.35], [58.80, 83.00], [59.05, 83.45], and [59.25, 83.65] PJ of jet fuel would be used in periods 1–5, respectively. Variations in jet fuel consumption would be mainly caused by fluctuations in end-user demands and improvements in technological efficiencies. Moreover, in the transportation sub-sector, a certain amount of energy would be allocated for recreational activities. In period 1, [10.85, 15.35], [24.45, 34.60], and [8.15, 11.55] PJ of diesel, gasoline and electricity would be consumed by recreational activities, respectively. In the next four periods, supplies of these three energy resources would change slightly to [10.10, 14.30], [23.60, 33.35], and [7.85, 11.10] PJ in period 2, [9.00, 12.65], [21.55, 30.35], and [7.20, 10.10] PJ in period 3, [8.00, 11.25], [19.60, 27.60], and [6.55, 9.20] PJ in period 4, and [7.10, 10.00], [14.75, 20.85], and [5.90, 8.35] PJ in periods 5, respectively. Over the planning horizon, the consumption of energy resources for recreational activities would gradually decrease. This is not caused by the declination of end-user demands but by the improvements of utilization efficiencies. Furthermore, for lubricants in the transportation sub-sector, the total consumed amounts would be [2.55, 3.55], [2.75, 3.85], [2.90, 4.05], [2.95, 4.20], and [3.40, 4.80] PJ in periods 1–5, respectively. Additionally, in order to meet energy demands for railroad transportation in the transportation sector, diesel, gasoline, and electricity would be supplied. Among them, electricity would be the primary contributor. In period 1, the amount of electricity adopted for railway transportation would be [19.10, 26.95] PJ, followed by diesel ([7.15, 10.10] PJ) and gasoline ([4.00, 5.60] PJ). In the next four periods, energy allocation to railway transportation would be relatively stable except for slight variations. Over periods 2–5, [6.00, 8.45], [5.10, 7.20], [4.45, 6.30], and [4.00, 5.65] PJ of diesel, [3.00, 4.20], [2.40, 3.35], [2.00, 2.80], and [1.70, 2.45] PJ of gasoline, as well as [177.40, 24.50], [15.95, 22.45], [14.60, 20.60], and [12.05, 17.00] PJ of electricity would be consumed in this sub-sector, respectively. Such declinations in energy consumption could be due to the fluctuations of end-user demand forecasting, and the upgrade of end-user technologies.

3.2.5. Industrial sub-sector

In the industrial sector, major industries that are considered in this research cover agriculture, forest, mining, construction, pulp and paper, and other manufactures. Similar to the transportational sub-sector, the same assumption is assigned that climate change would not have significantly direct impacts on the industrial sub-sector in Manitoba. Major energy resources in this sector would include natural gas, fuel oil, LPG, coal, renewable and wood waste, as well as electricity. Overall, coal and electricity would be the primary resources being used in the industrial sector (Fig. 21). The largest contributor to energy consumption in the industrial sector would be electricity. In periods 1–5, [361.50, 510.30], [325.55, 459.65], [304.90, 430.40], [283.55, 400.30], and [262.10, 370.00] PJ of electricity would be utilized in this sub-sector, respectively. A large amount of coal would also be used in the industrial sub-sector ([209.25, 295.40], [191.85, 270.85], [179.85, 253.95], [168.25, 237.50], and [155.20, 219.00] PJ over the planning horizon, respectively). The total amount of natural gas consumed by the industrial sub-sector would be [62.40, 88.10], [54.30, 76.65], [48.15, 67.95], [47.35, 66.85], and [43.15, 60.90] PJ over periods 1–5, respectively. Also, [112.80, 159.20], [97.40, 137.50], [86.50, 122.15], [77.85, 109.85], and [74.00, 104.35] PJ of fuel oil would be consumed over periods 1–5, respectively. Moreover, a certain amount of renewable energies would be used, i.e., [26.95, 38.00], [18.10, 25.55], [17.90, 25.20], [17.60, 24.80], and [17.50, 24.70] PJ over the planning horizon. Generally, the total energy allocated to the industrial sector in Manitoba would gradually decrease accompanied by end-user demand fluctuations and technology efficiency improvements.

For agricultural activities, the primary energy resource would be electricity, followed by renewable energy resources, natural gas, and fuel oil. In the first period, [41.45, 58.55], [15.55, 21.95], [10.35, 14.65], and [3.10, 4.40] PJ of electricity, renewable energy resources, natural gas, and fuel oil would be consumed by the agricultural activities. Over the next four periods, consumption of electricity and natural gas would decrease slightly, while those of fuel oil and renewable energy resources would increase by a certain amount. Over periods 2–5, [8.95, 12.65], [8.05, 11.35], [10.75, 15.20], and [9.75, 13.80] PJ of natural gas would be consumed by agricultural activities, respectively. As for fuel oil, [3.50, 4.95] and [4.00, 5.70] PJ would be utilized in periods 2 and 3, respectively; the consumption would decrease to zero over the next two periods. The utilization of renewable energies would increase slightly in the agriculture of the province. In detail, the consuming amounts would be [15.70, 22.20], [16.10, 22.50], [16.15, 22.80], and [16.30, 23.00] PJ over periods 2–5, respectively, representing a gradually increasing share among the total energy consumption by agriculture. As for the adoption of electricity, the amounts would be [38.65, 54.60], [36.75, 51.90], [34.45, 48.65] and [32.55, 45.95] PJ over periods 2–5, respectively.

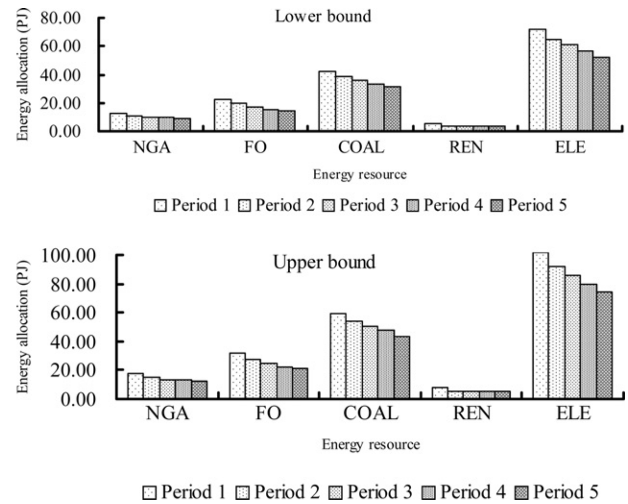

Fig. 21. Energy allocations to the industrial sub-sector over periods 1–5.

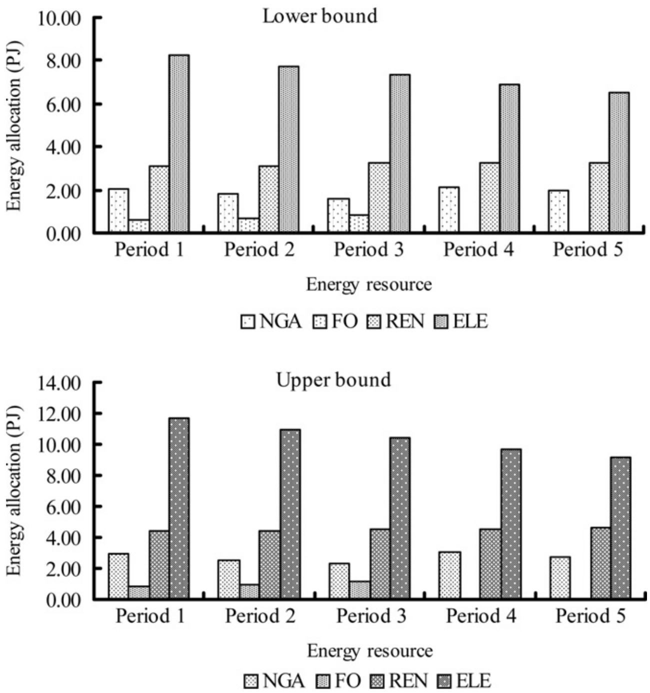

Fig. 22. Energy allocation to agriculture over periods 1–5.

Generally, the energy consumption structure for agriculture would be quite stable over the entire planning horizon except for during a slight transition to renewable energy resources (Fig. 22).

In the forest industry of the industrial sub-sector, natural gas, fuel oil, LPG, renewable energies and wood waste, and electricity would be employed. Similar to the agriculture, electricity and renewable energies would be the main sources of energy supply. In periods 1–5, [3.60, 5.05], [2.40, 3.35], [1.80, 2.50], [1.45, 2.00], and [1.20, 1.70] PJ of renewable energies, and [2.49, 3.35], [2.25, 3.15], [2.10, 2.95], [2.00, 2.75], and [1.85, 2.60] PJ of electricity would be allocated to forest-related activities in Manitoba. The remaining energy consumption would be covered by natural gas ([1.20, 1.70] PJ over the entire planning horizon) and fuel oil ([1.20, 1.70], [0.95, 1.35], [0.80, 1.10], [0.70, 0.95], and [0.60, 0.85] PJ in periods 1–5, respectively). There would be no LPG consumption over the planning horizon.

For the mining industries in the industrial sub-sector, natural gas, fuel oil, coal and electricity would be supplied (Fig. 23). Among them, coal and electricity would be the primary energy resources. In periods 1–5, [30.90, 43.65], [28.50, 40.20], [25.05, 35.40], [21.90, 30.90], and [19.15, 27.00] PJ of coal would be used,

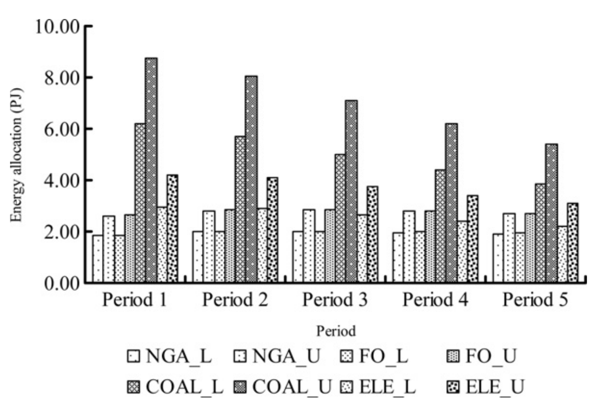

Fig. 23. Energy allocation to mining industries over periods 1–5.

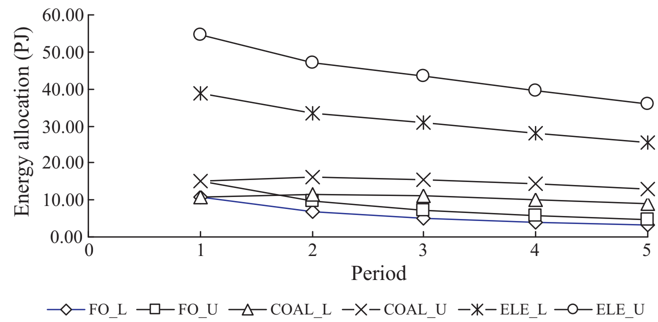

Fig. 24. Energy allocation to pulp and paper industries over periods 1–5.

respectively. The gradual reductions in coal consumption represents the steady implementation of more rigid restrictions on coal utilization. This would eventually phase out coal use in this sub-sector. Over the same periods, [14.85, 20.95], [14.50, 20.45], [13.35, 18.85], [12.10, 17.10], and [10.95, 15.45] PJ of electricity would be allocated to the mining industries. In total, [9.30, 13.10], [10.00, 14.10], [10.05, 14.15], [9.85, 13.90], and [9.60, 13.50] PJ of natural gas and [9.35, 13.20], [10.05, 14.15], [10.10, 14.20], [9.90, 13.95], and [9.65, 13.60] PJ of fuel oil would be allocated to this sub-sector in periods 1–5, respectively.

In the construction of the industrial sub-sector, the adopted energy resources would include fuel oil ([3.90, 5.50], [6.25, 8.85], [2.75, 3.90], [2.40, 3.35], and [2.15, 3.00] PJ over periods 1–5, respectively), renewable energies ([7.80, 10.10] PJ in period 1 and 0 PJ over periods 2–5), and electricity ([12.25, 17.60], [11.35, 16.05], [12.40, 17.50], [11.55, 16.35], and [10.95, 15.45] over periods 1–5, respectively). In terms of energy allocation to pulp and paper industries, major energy resources would include fuel oil, coal, and electricity. In this sub-sector, electricity would be the primary resource being consumed. In period 1, [193.40, 273.05] PJ of electricity would be consumed, accounting for over 60.00% of the total energy consumed in the sub-sector of pulp and paper industries. For the remainder of the planning horizon, electricity would still be the primary energy resource ([166.90, 235.65], [153.70, 216.90], [140.00, 197.65], and [126.70, 178.90] PJ in periods 2–5, respectively). Fuel oil and coal would be responsible for the rest of the energy demands in this sub-sector. In detail, [53.75, 75.85], [34.00, 48.00], [25.60, 36.15], [20.20, 28.55], and [16.45, 23.20] PJ of fuel oil and [53.75, 75.85], [56.65, 80.00], [54.90, 77.45], [50.55, 71.40], and [45.65, 64.40] PJ of coal would be consumed in the sub-sector of pulp and paper industries in periods 1–5 (Fig. 24).

In the industrial sub-sector of Manitoba, there would be a large quantity of energy resources allocated to other manufacturing industries. In periods 1–5, [41.55, 58.65], [34.15, 48.20], [28.85, 40.75], [25.55, 36.05], and [22.60, 31.90] PJ of natural gas would be supplied to these industries. In addition to natural gas, fuel oil, coal and electricity would be employed. Over the planning horizon, electricity would be the primary resource. In detail, [96.90, 136.80], [91.90, 129.75], [86.60, 122.30], [83.45, 117.80], and [77.60, 111.65] PJ of electricity would be used over periods 1–5, respectively. Variations in electricity and natural gas consumption would be due to two major reasons: (i) fluctuations of the end-user projection and (ii) improvements in relevant technology efficiencies. The consumption of coal would drop gradually over the planning horizon, while the consumption of fuel oil would increase slightly. In detail, [41.55, 58.65] PJ of fuel oil and [124.60, 175.90] PJ of coal would be required in period 1 for the sub-sector of other manufactures in the province. Then, over periods 2–5, the allocation amounts for fuel oil and coal would change to [42.70, 60.25] and [106.70, 150.65], [43.30, 61.15] and [99.90, 141.10], [44.70, 63.10] and [95.80, 135.20], and [45.20, 63.80] and [90.40, 127.60] PJ, respectively (Fig. 25).

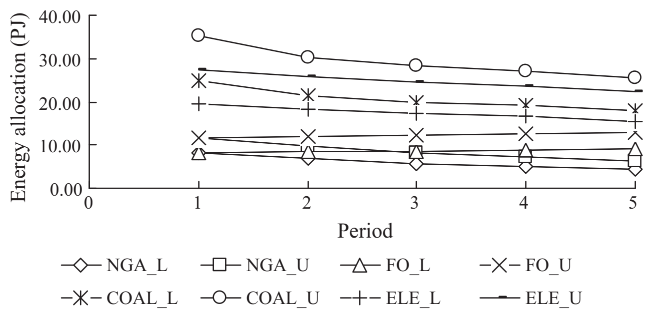

Fig. 25. Energy allocation for other manufactures over periods 1–5.

Obviously, based on the application results of the proposed integrated modeling system (IMS) in the province of Manitoba, energy management systems planning, uncertainty analysis, climate change identification and analysis, and adaptation planning can be seamlessly integrated into a general framework. Also, the fuzzy-interval inference method (FIIM) and the inexact energy model (IEM) can be successfully linked together to reflect and address multiple level uncertainties associated with adaptation planning towards climate change within a provincial energy management system that is heavily dependent on renewable energy resources. In detail, the proposed modeling system can effectively enhance the previous studies in the areas of EMSs planning, uncertainty analysis, climate change impact analysis and adaptation planning, including: (i) optimal allocations of multiple technologies, multiple resources and multiple sub-sectors within an energy management system can be effectively incorporated into a general modeling system, (ii) interactions among various policies and strategies related to EMSs under changing conditions can be effectively addressed, (iii) mitigation policies and adaptation schemes under climate change can be successfully linked within a energy management system, (iv) integrated impacts of climate change on multiple energy sub-sectors (such as end-user energy demands and energy supply facilities) can be systematically reflected and incorporated within the modeling formulation, solution procedure and result interpretation, (v) multiple levels of uncertainties associated with climate change impact analysis, impact interactions, and adaptation planning can be successfully reflected and handled, enhancing conventional methodologies in dealing with impact analysis and adaptation planning, (vi) a series of practical solutions related to energy management systems planning, climate change adaptation schemes and their linkage can be generated and provide for decision support, and (vii) the obtained results indicated that the proposed methodologies are effective in identifying planning policy baselines as well as including those under changing climatic conditions.

4. Conclusions

In this study, a large-scale integrated modeling system (IMS) was applied for supporting climate change impact analysis and adaptation planning of the energy management system in the Province of Manitoba, Canada. The system was based on the integration of the fuzzy-interval inference method (FIIM), inexact energy model (IEM), and uncertainty analysis. The integrated climate change impact levels and the corresponding optimal adaptation strategies were investigated through FIIM and IEM. Useful solutions were generated, reflecting complex tradeoffs among various administrative objectives in the province as well as political and economic efforts in adapting to climate change. Also, the uncertainties associated with climate change impact analysis and adaptation planning can be successfully addressed and incorporated within modeling formulation and result solving processes, improving robustness of the optimal strategies. The results indicated that adaptation schemes should respond to different levels of climate change impacts on both energy demand and supply in this province due to its high dependence on renewable energy resources. The results also suggested that energy allocation/production patterns in the residential, commercial, and power-generation sub-sectors would be sensitive to climate change. Thus, integrated impacts of climate change as well as the corresponding adaptation schemes could be easily identified within a systematic context in the province.

Moreover, the obtained interval solutions would be helpful for supporting (a) the adjustment or justification of the existing allocation patterns of energy resources and services, (b) the long-term planning of renewable energy utilization, (c) the formulation of local policies regarding energy consumption, economic development, and energy structure, (d) the analysis of interactions among economic cost, system efficiency, emission mitigation, and energy-supply security, and (e) the investigation of system vulnerability and responses towards various levels of impacts under climate change. Thus, IMS could provide an effective technique for decision makers in examining and visualizing integrated impacts of climate change on energy management systems as well as identifying desired adaptation strategies under multiple levels of uncertainties.

Acknowledgements

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